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Robo Raven: A Flapping Wing Air Vehicle with Compliant and Independently Controlled Wings

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Research Interests

- Computational Foundations for Automation
  - Computer Aided Design
  - Manufacturing Automation
  - Robotics
- Current Focus
  - Exploiting synergy between robotics and manufacturing

The Role of Robotics in Advanced Manufacturing

- Robots have been used to improve manufacturing on high volume production lines
  - Reduce labor cost
  - Increase production rate
  - Increase quality
- Use of robots is currently very limited

(Image Source: ATACO Steel Products)

New opportunities for deploying robots in manufacturing

Robotic Assembly at Small Size Scales

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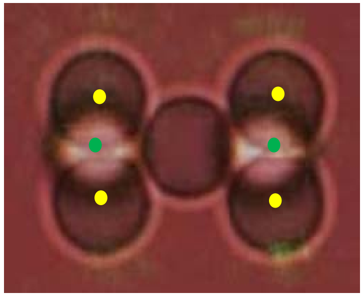
Assembly at Microscale:
Optical Micromanipulation



Assembly at Mesoscale:
In-Mold Assembly

Robots look and behave differently

Human Robot Collaboration in Bin Picking and Assembly

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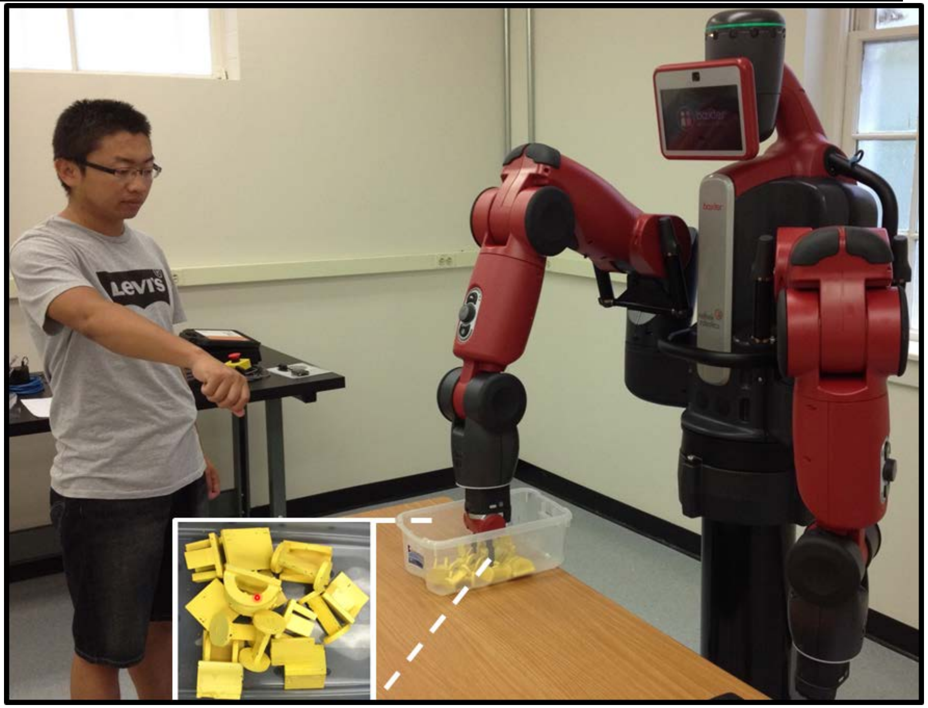
- Bin-picking precedes assembly in many low volume production scenarios
- Challenges
  - Random part postures, overlaps, occlusions, background clutter, shadows, poorly lit conditions
- Approach



  - Robot does bin-picking and assembles each part to build the product
  - Human assists robot in critical situations by (1) resolving perception and/or grasping problems encountered during bin-picking and (2) performing dexterous manipulation required during assembly

Learning from Human Demonstrations

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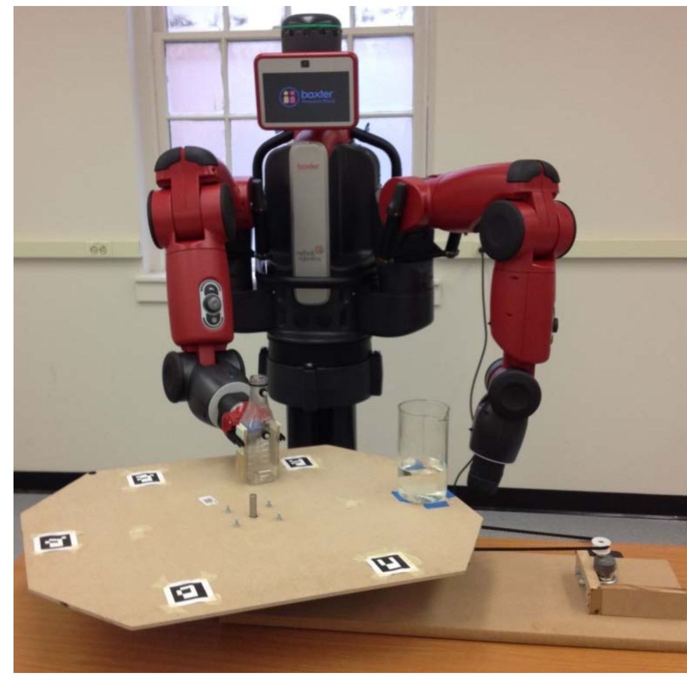
- Approach allows learning from successful human demonstrations, errors made by humans, and how humans recovered from these errors in subsequent trials
- Classifiers and iterative search to generate initial task parameters for robot
- If robot fails, simple rules are learned to refine them by capturing how humans change parameters to transition from failure to success



J. D. Langsfeld, K. N. Kaipa, R. J. Gentili, J. A. Reggia, and S. K. Gupta. Incorporating failure-to-success transitions in imitation learning for a dynamic pouring task. *Workshop on Compliant Manipulation: Challenges and Control*, held at *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014)*, Chicago, IL, September 18, 2014.

Ensuring Human Safety in Hybrid Cells

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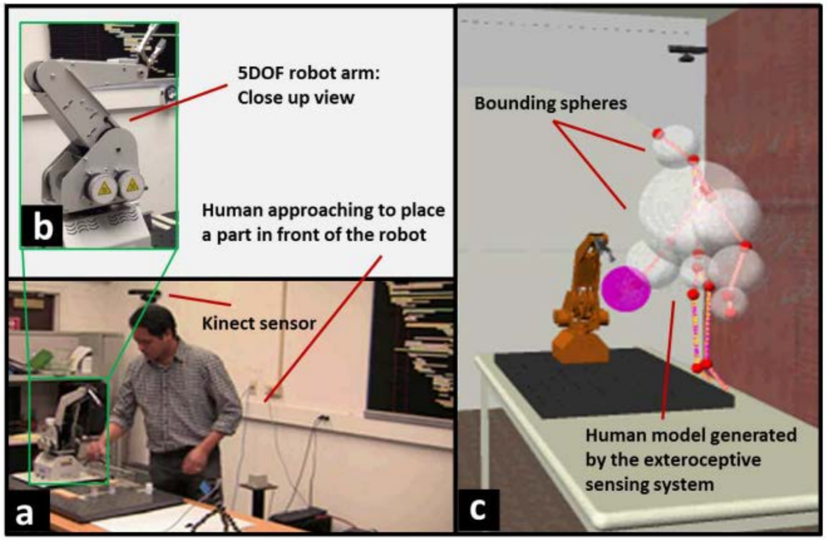
- Real-time replication of human and robot movements inside a physics-based simulation of the work cell
- Multiple Kinects based system to track and model human
- Roll-out strategy



  - forward-simulate robot’s trajectory and create temporal set of its postures for next few seconds
  - Check whether any of these postures collide(s) with human model
- Pause robot’s motion whenever imminent collision detected

Morato, C., Kaipa, K.N., Zhao, B., and Gupta, S.K. (2014). Toward safe human robot collaboration by using multiple Kinects based real-time human tracking. *Journal of Computing and Information Science in Engineering*, 14(1):011006-011006-9.

See Videos

https://www.youtube.com/watch?v=qg0kjzrag1I

https://www.youtube.com/watch?v=X68F9p8DMLg

The Role of Advanced Manufacturing in Robotics

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- Additive Manufacturing
- Polymer Composites
- In-Mold Assembly
- Microfabrication

Stratasys 3D Printer

Advances in manufacturing can be used to realize improved robot designs

How to Realize Bio-Inspired Robots?

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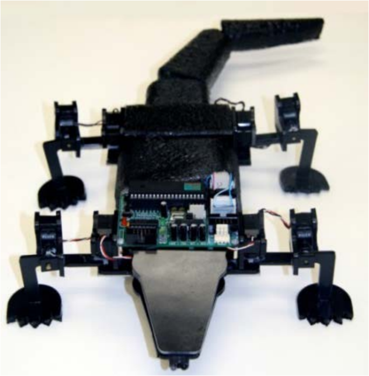
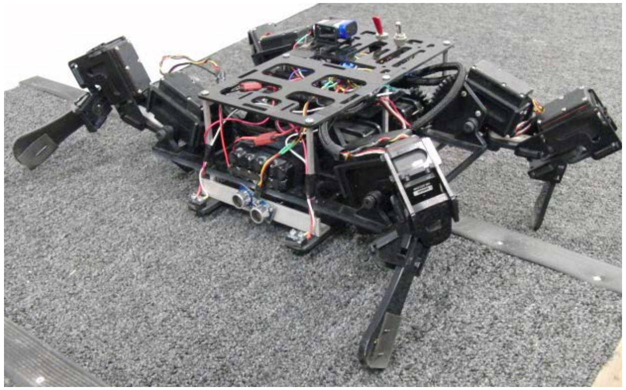

NaviGator


RoboTerp


ScaleBot


R2G2

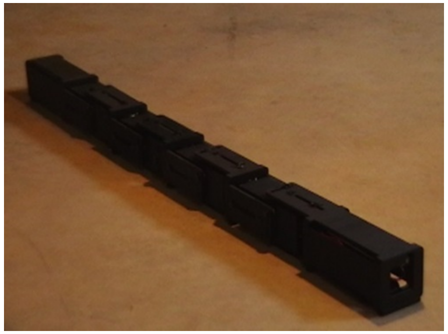

RoboCrab


RoboRaven

R2G2:

Robot with Rectilinear Gait for Ground Operations

- Goal: Create a limbless robot with high forward velocity and small cross section
- Approach
  - New Rectilinear Gait
  - Compact Parallel Mechanism
  - Additive Manufacturing
  - Design Details
    - Cross Section: 70 x 70 mm
    - Length (Contracted): 1000 mm
    - Length (Extended): 1385 mm
    - Weight: 2.5 kg



See Video at

https://www.youtube.com/watch?v=t4oQos_LYyc

J.K. Hopkins and S.K. Gupta. Design and modeling of a new drive system and exaggerated rectilinear-gait for a snake-inspired robot. *ASME Journal of Mechanism and Robotics*, 6(2):021001, 2014.

Robo Terp

- Goal: Develop a legged amphibious robot for splash free swimming
- Approach
  - Incorporate compliance in legs to assist swimming
  - Optimize leg design
  - Develop new gaits for walking, swimming, and transitioning
  - Develop sensors for autonomous gait transitions

See Video at

https://www.youtube.com/watch?v=X9IV7QDcJRg

A. Vogel, K.N. Kaipa, G. Krummel, H.A. Bruck, and S.K. Gupta. Design of a compliance assisted quadrupedal amphibious robot. *IEEE International Conference on Robotics and Automation (ICRA 2014)*, Hong Kong, China, May 31-June 7, 2014.

Robo Crab

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- Goal: Develop a self-righting robot Inspired by horseshoe crabs
- Approach
  - Built for surf zone traversal
  - Walks on sand, in water
  - Self-rights when tipped over
  - Fully waterproof

See Video at

https://www.youtube.com/watch?v=L-J3NW3sXY8\

G. Krummel, K.N. Kaipa, and S.K. Gupta. A horseshoe crab inspired surf zone robot with righting capabilities. *ASME Mechanism and Robotics Conference*, Buffalo, NY, August 2014.

SCALE Bot

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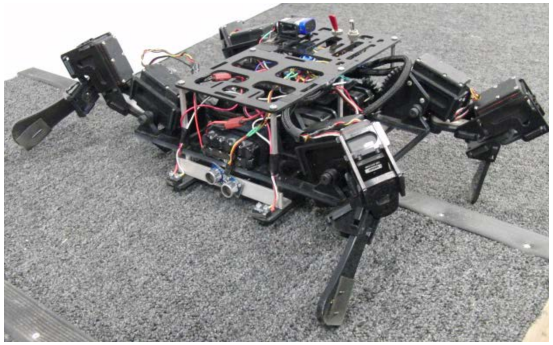
- Goal: Develop a low-cost robot capable of autonomously climbing stairs using on-board sensing and computation
- Approach
  - Develop twelve degree of freedom legged robot using off the shelf actuators, sensors, and controllers
  - Develop parameterized gaits to climb stairs
  - Develop algorithms to process sensor data to select gait parameters



See Video at

https://www.youtube.com/watch?v=BDSzO8mhOuY

Flapping Wing Air Vehicles

Robotic Birds: Motivation

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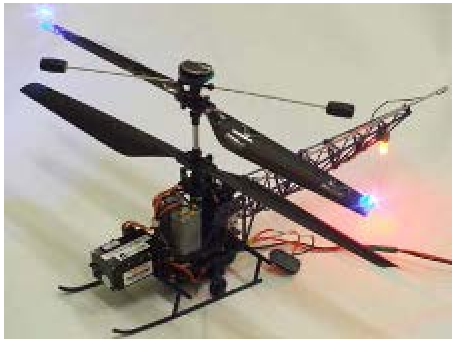
- Attributes of fixed wing flight
  - High forward speeds required for generating lift
  - Low maneuverability
  - Difficult to operate in confined spaces



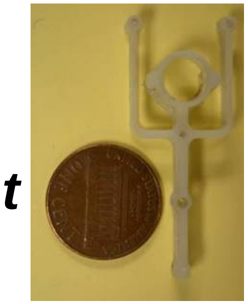
- Attributes of rotary wing flight
  - Low forward speeds and hovering possible
  - High frequency leads to noisy operation

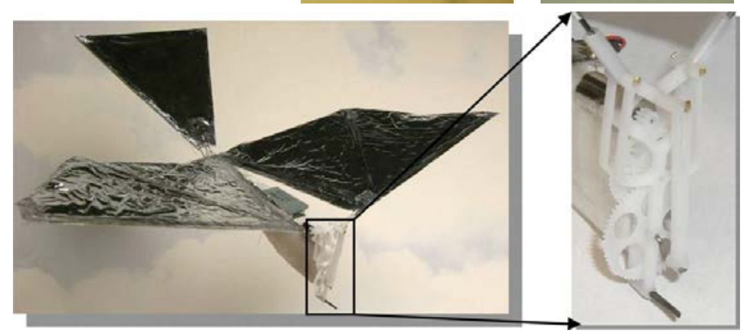
- Attributes of flapping wing flight
  - Low frequency flapping leads to quiet flight
  - Low forward speeds lead to high maneuverability
  - Bridges gap between fixed and rotary wing

First Effort: Small Bird (2005-2007)

- Goal: Develop a lightweight and efficient drive mechanism to transmit power from the motor to wings
- Approach
  - Develop a new compliant mechanism concept
  - Develop multi-piece molds to realize the light weight compliant mechanism
  - Optimize shape
  - Incorporate multi-functional materials for dissipating heat

First Flight in 2007





Weight: 9.7 g (excluding battery)

Wing Span: 34.3 cm

Flapping Frequency: 12.1 Hz

Pay Load Capability: 5.7 g (including battery)

D. Mueller, H.A. Bruck, and S.K. Gupta. Measurement of thrust and lift forces associated with drag of compliant flapping wing for micro air vehicles using a new test stand design. *Experimental Mechanics*, 50(6):725–735, 2010

W. Bejgerowski, A. Ananthanarayanan, D. Mueller, and S.K. Gupta. Integrated product and process design for a flapping wing drive-mechanism. *ASME Journal of Mechanical Design*, 131, 2009

W. Bejgerowski, S.K. Gupta, and H.A. Bruck. A systematic approach for designing multi-functional thermally conducting polymer structures with embedded actuators. *ASME Journal of Mechanical Design*, 131(11): 111009, 2009

Big Bird with Folding Wing (2007-2008)

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- Goal: Generate static lift by folding wings during up-strokes
- Approach
  - Increase the size of the platform to enhance payload capacity
  - Incorporate on-way joints in wings to facilitate passive wing folding in up-stroke
  - Develop new joint designs based on the distributed compliance concept
  - Optimize wing design

Weight: 29.9 g (excluding battery)

Wing Span: 57.2 cm

Flapping Frequency: 4.5 Hz

Pay Load Capability: 17.0 g (including battery)

First Flight in 2008

D. Mueller, J. Gerdes, and S.K. Gupta. Incorporation of passive wing folding in flapping wing miniature air vehicles. *ASME Mechanism and Robotics Conference*, San Diego, 2009

Jumbo Bird (2009-2010)

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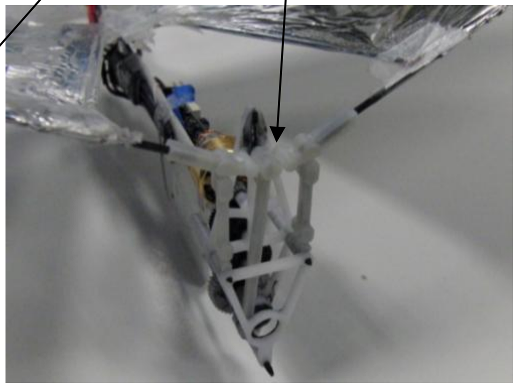
- Goal: Increase payload capacity of the robotic bird
- Approach
  - Develop a new transmission mechanism based on multi-material compliant mechanism concepts
  - Develop in-mold assembly process for realizing transmission mechanism
  - Concurrently optimize product and process parameters
  - Optimize wing designs

First Flight in 2010

Weight: 38.0 g (excluding battery)
Wing Span: 63.5 cm
Flapping Frequency: 6.1 Hz
Pay Load Capability: 33.0 g (including battery)

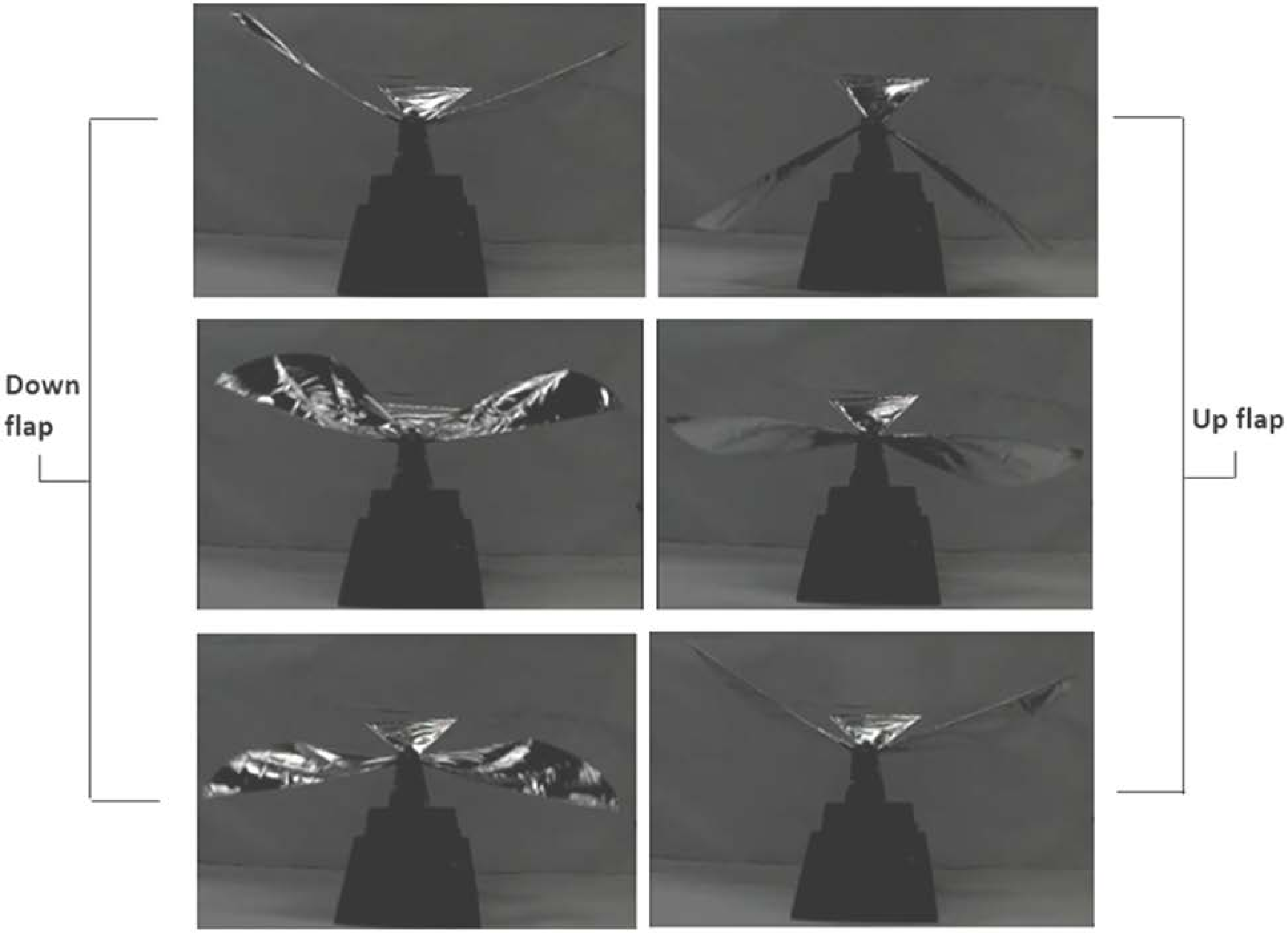


J.W. Gerdes, K.C. Cellon, H.A. Bruck, S.K. Gupta. Characterization of the mechanics of compliant wing designs for flapping-wing miniature air vehicles. *Experimental Mechanics*, Accepted 2013
W. Bejgerowski, J.W. Gerdes, S.K. Gupta, and H.A. Bruck. Design and fabrication of miniature compliant hinges for multi-material compliant mechanisms. *International Journal of Advanced Manufacturing Technology*, 57(5):437-452, 2011
W. Bejgerowski, J.W. Gerdes, S.K. Gupta, H.A. Bruck, and S. Wilkerson. Design and fabrication of a multi-material compliant flapping wing drive mechanism for miniature air vehicles. *ASME Mechanism and Robotics Conference*, Montreal, Canada, August 2010

See Video at

https://www.youtube.com/watch?v=qJmeFKf0l-g

Robotic Birds: Observations



Wings undergo through significant deformation!

Main Limitations of Previous Designs

- Wing velocity has significant influence on wing deformation
- No way for us to control wing deformation by controlling velocity in previous designs
  - We can only control flapping frequency

Need to control wing shape by controlling wing velocity

New Direction in Research

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- Develop robotic bird with *Independently Controllable* and *Programmable Wings* to understand bio-inspired flight
  - Understand the influence of wing velocity on lift and thrust forces
  - Optimize performance
  - Aerobatic maneuvers

Robo Raven
(Joint Project with Dr. Hugh Bruck)

Our Inspiration: Raven

Raven Specs	
Length:	24 to 26 in (61 to 66 cm)
Wingspan:	45.6 to 56.4 in (1.2 to 1.4 m)
Weight:	2.3 lbs (1.3 kg)
Flapping frequency:	4-6 Hz

http://www.birdsource.org/gbbc/gallery/2007/comrav_tucker-cr_nm.jpg/image_preview

Research Challenges

- Independent wing control means two independent actuators → heavier platform
- Wing and motor must be properly matched to enable flight
  - Optimal wing design
  - Run motors at optimal operating point
- Difficult problem to model at system level

Flapping Profile	Motor Dynamics	Compliant Wings	Unsteady Aerodynamics

Wing Design

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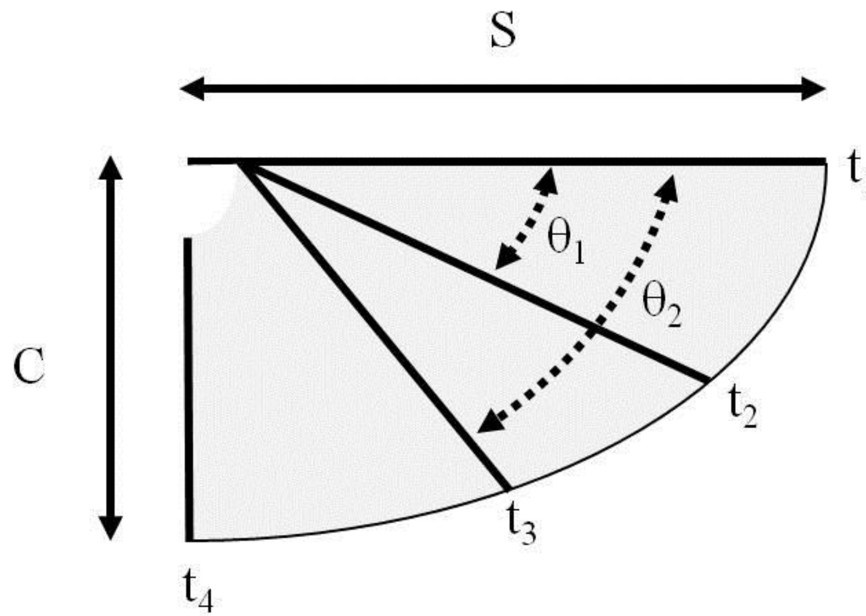
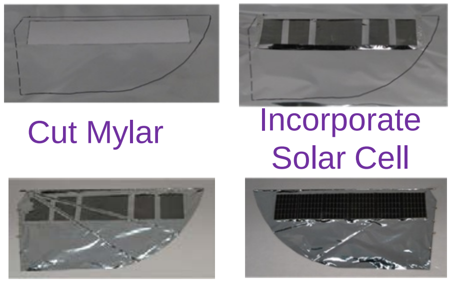


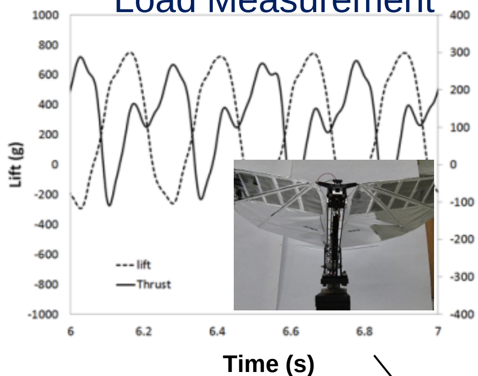
- Mylar foil and carbon fiber stiffeners
- Passive deformation in response to loading
- Many iterations to get correct deformation, used high speed imaging and load cell data to evaluate

Approach

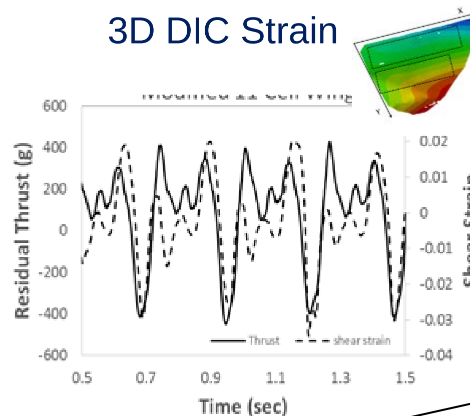
Additive manufacturing multi-material sheets



6DOF Dynamic Load Measurement



3D DIC Strain



Programmable Wings

New additive manufacturing process for incorporating *flexible solar cells* in thin complaint structures

Lift and thrust models for compliant flapping wings by performing experimental characterization

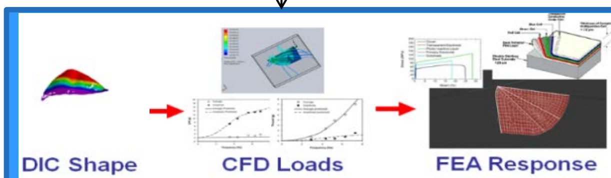
Lift: $F_L = \int C_D \rho v^2 \cos(\theta)\, dA$

Thrust: $F_T = \int C_D \rho v^2 \sin(\theta)\, dA$

Analytical multifunctional flight performance models based on energy and payload

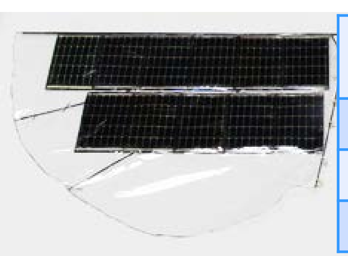
Flight Time: $T' = k_b(k_1 k_2 F_l/g - M_m - M_s)/(P - k_s M_s)$

Recharge Time: $T_r = f_d k_b(k_1 k_2 F_l/g - M_m - M_s)/k_s M_s$



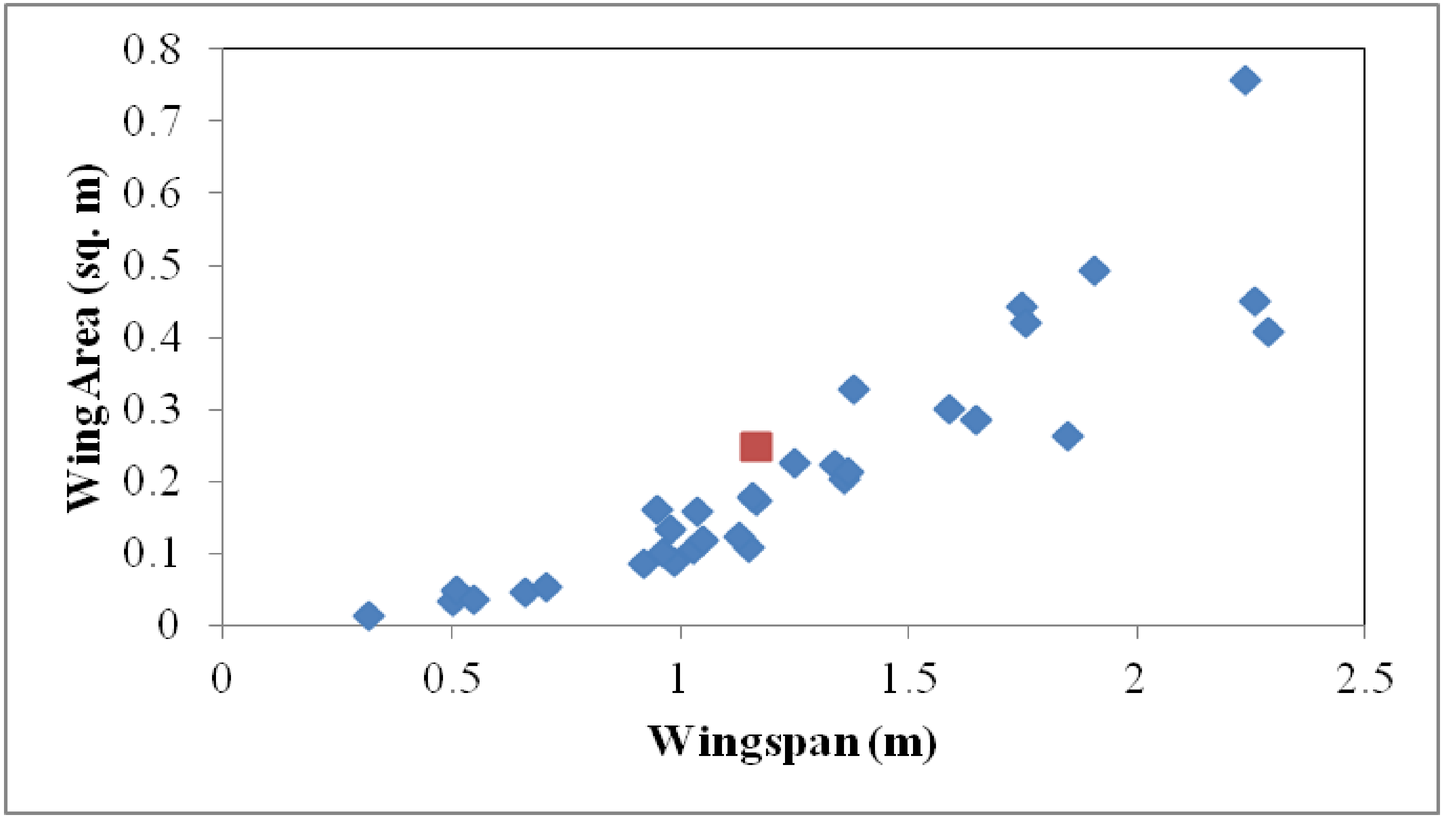
Parameterized multifunctional wing model using DIC/CFD/FEA

System Level Optimization for Autonomous Flight



	Power Consumption	Solar Power Generation	Predicted Increase in Flight Time		Measured Increase in Flight Time	
	W	W	Time (sec)	%	Time (sec)	%
Regular UAV	35.8	4.10	n/a	n/a	n/a	n/a
22 Module UAV	37.0	7.41	41.9	15.4	38.1	14.1

Wing Sizing



Robo Raven wing area and wingspan (red) compared to 33 other birds (blue)

Selected Wing

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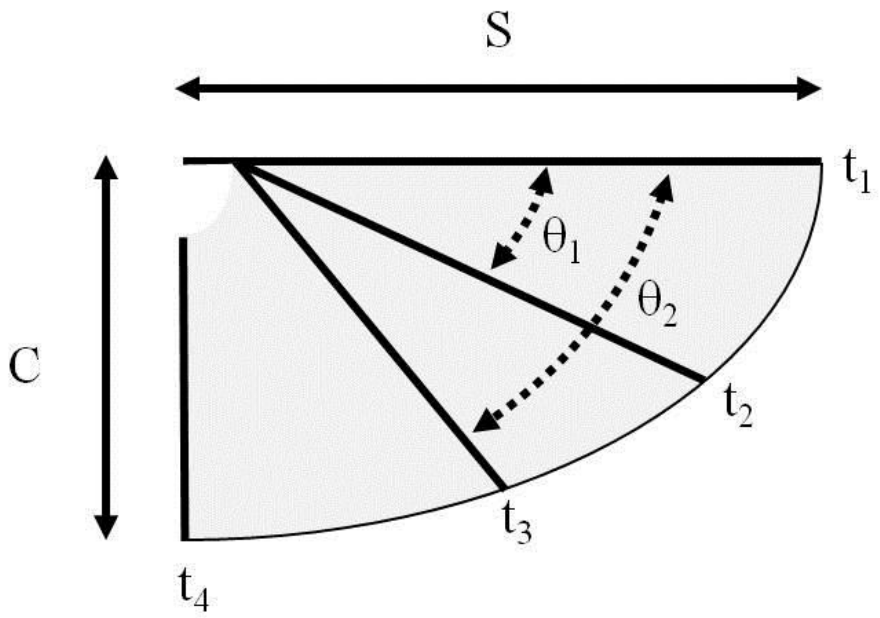

Parameter	Value
S	23.85”
C	14.25”
t_1	0.125”
t_2	0.064”
t_3	0.064”
t_4	0.064”
θ_1	20.5°
θ_2	43°

Flapping Range: 70 degrees

Flapping Frequency: 4 Hz

Result: Robo Raven Flying Prototype

- Fabricated using additive manufacturing
- Independently controlled wings capable of arbitrary gaits
- New maneuvers possible: flips, dives, gliding
- Vehicle weight = 264.5g
- Flight speed = 6.7 m/s
- Endurance = 4 minutes 45 seconds

Comparison with Ravens

Raven Specs		Robo Raven Specs	
Length:	24 to 26 in (61 to 66 cm)	Length:	24 in (61 cm)
Wingspan:	45.6 to 56.4 in (1.2 to 1.4 m)	Wingspan:	44 in (1.1 m)
Weight:	2.3 lbs (1.3 kg)	Weight (w/battery, w/out):	(291.6 g, 264.5 g)
Flapping frequency:	4-6 Hz	Flapping frequency:	4 Hz

See Video at

https://www.youtube.com/watch?v=mjOWpwbnmTw

Flight Power Comparison

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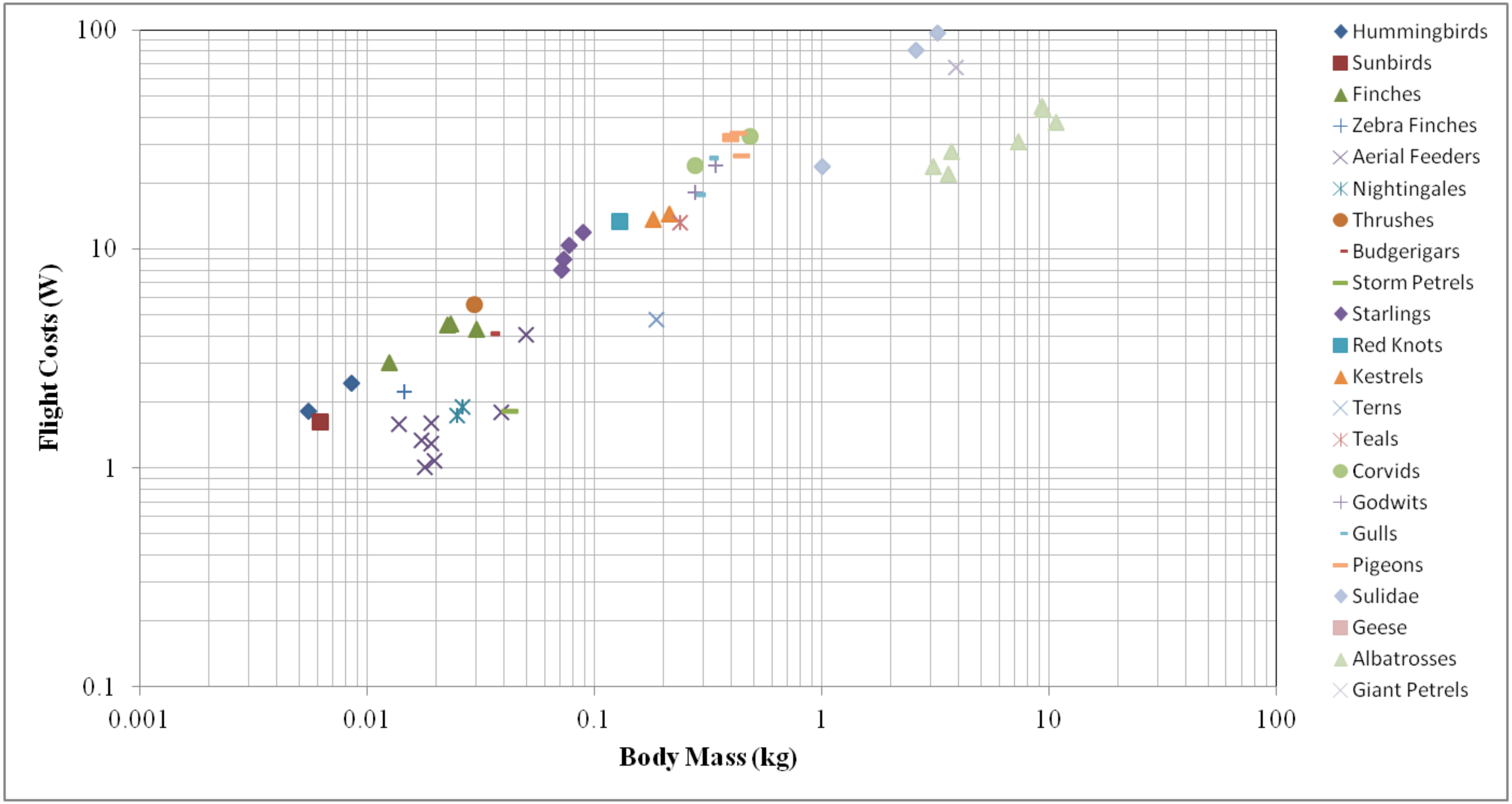

J. J. Videler, *Avian Flight*. Oxford: Oxford University Press 2005.

Flight cost of 33 species of birds

Robo Raven II
(Work done in Collaboration with ARL)

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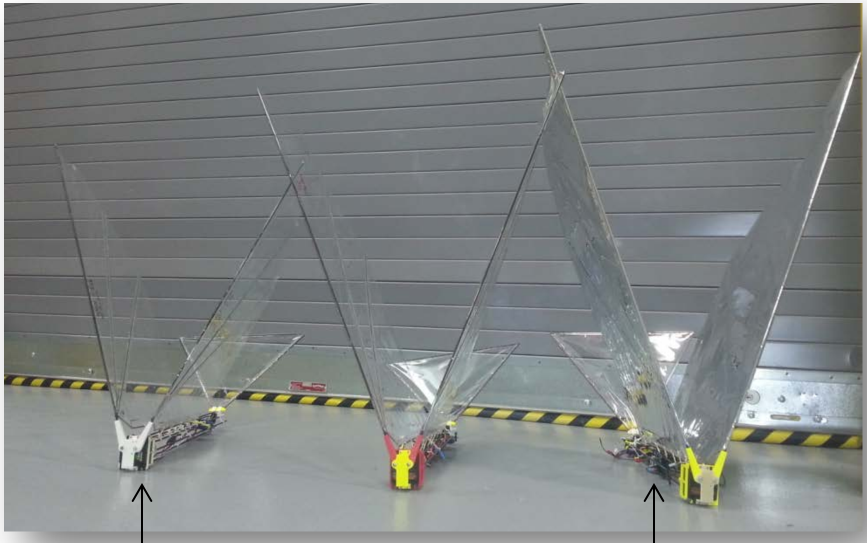
- Goal: Increase system-level performance through subsystem modeling and optimization
- Approach
  - Dynamometer motor testing
  - Expand to a family of wing sizes
  - Select wing size and flapping gait to improve performance by matching to the motor
  - Increased payload used to lift batteries or larger payload
  - Characteristics
    - Max weight = 350g
    - Endurance = ~20 minutes

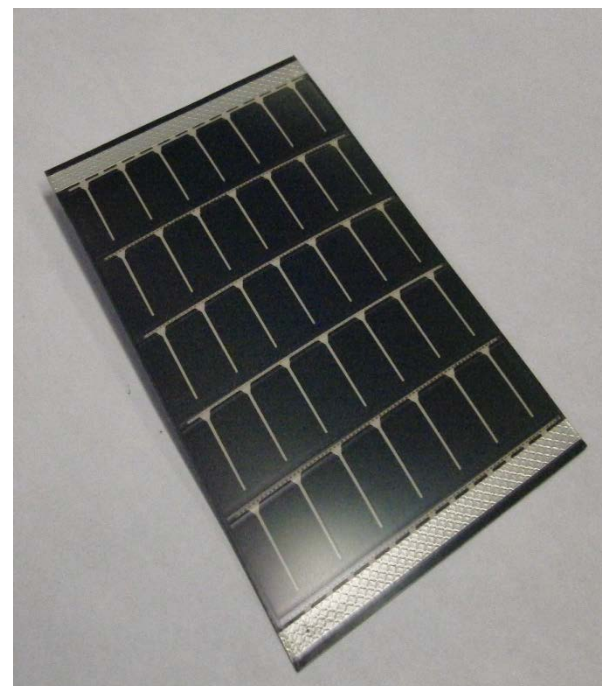


See Video at
https://www.youtube.com/watch?v=q6ga9hxm6FY

Robo Raven III

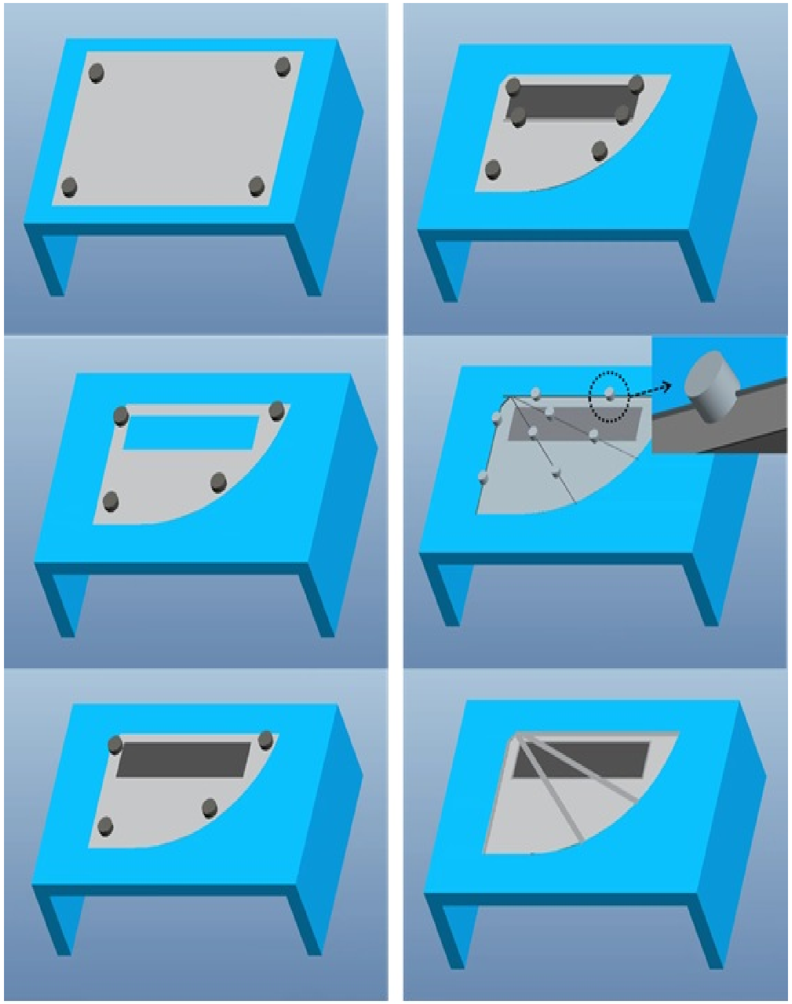
Multifunctional Wings

- Limitations in flight time are caused by small batteries due to payload limitations
- Multifunctional wings with integrated solar cells that harvest energy
  - Assist the battery during flight
  - Recharge the battery using solar power



Development of Robo Raven III

- A new wing manufacturing technique was developed to fabricate the solar cell wings
- Solar panels:
  - Each wing contains a panel of 6 MPT6-75 solar cell modules from Powerfilm's©. These flexible 7.3 x 11.4 cm solar cells run at 6 V and produce 50 mA of current
  - Each wing is capable of producing 1.8 Watts for a total of 3.6 Watts
- A layered manufacturing process is used to integrate the panels into the wing



Power Gains

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- The current battery is a two cell Lithium Polymer (LiPo) battery rated at 25 C.
- Robo Raven depletes the battery in 4.75 minutes using an average of 34.6 Watts
- The solar cells produce 3.6 Watts
- The solar cells can only be used to extend the flight time by assisting the battery or recharge the batteries between flights
- The new maximum flight time recorded with the solar celled wings was 5.48 minutes, a 15.3% increase

Performance Characterization

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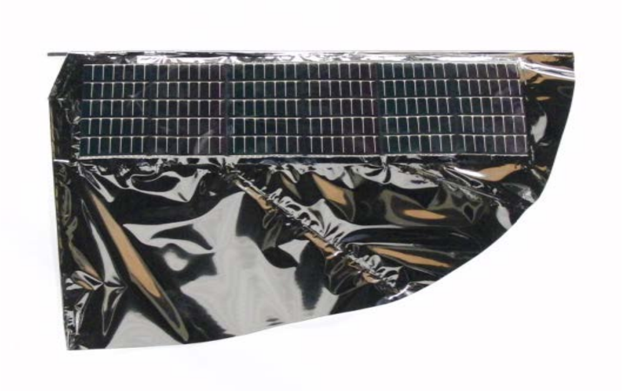
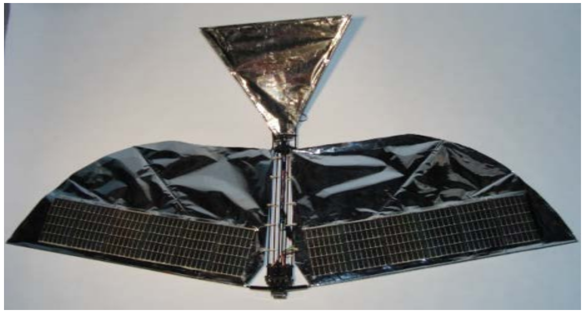
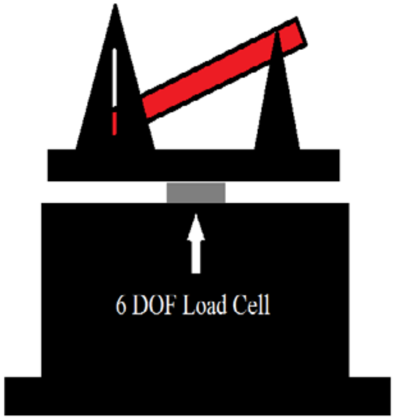
- The integration of solar cells is expected to have an effect on vehicle performance
- The increase in mass and stiffness of the wings will alter how the wing deform thus alter the performance
- Load cell testing was conducted to identify the differences in lift and thrust production by each wing design
- Digital Image Correlation was also used to determine the differences in wing deformation between the two wing designs

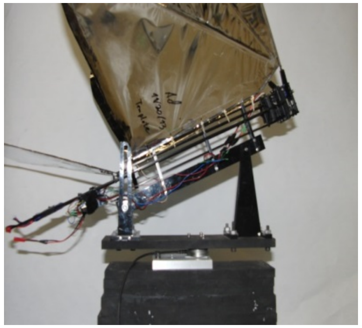




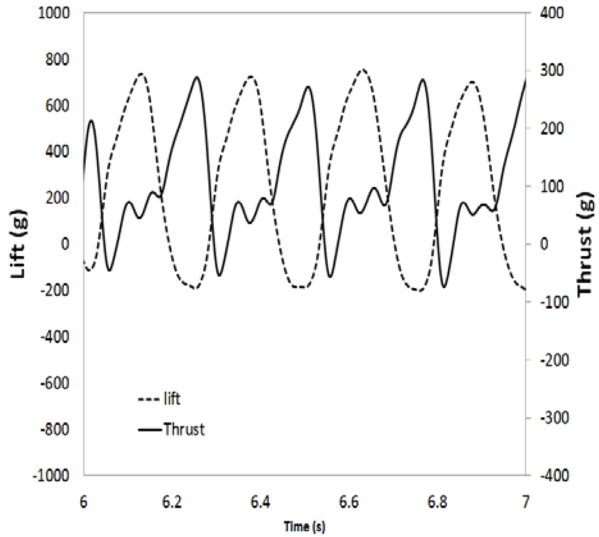
Load Cell Testing



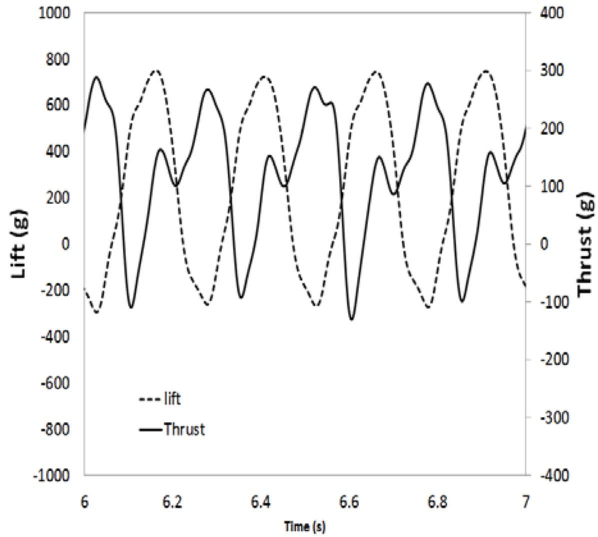
- Using a 6 DoF force transducer, mounted on a test stand, the aerodynamic lift and residual thrust forces were measured while flapping.
- The UAV was angled at a 20 deg. incline, inside of a wind tunnel operating at 5 m/s
- The 12 cell Wings produced 5 more grams of residual thrust and 11 more grams of aerodynamic lift



Wing	Residual Thrust (grams)	Lift (grams)
Regular	113	240
12 Cell	118	251



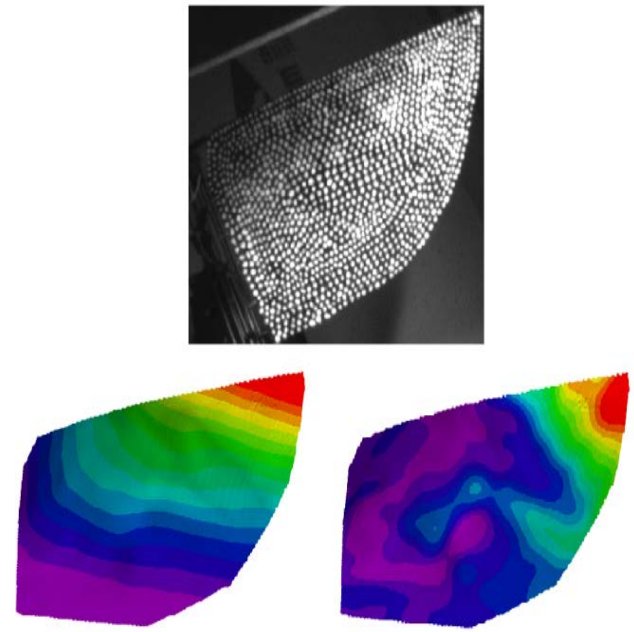
Regular Wings



Solar Cell Wings

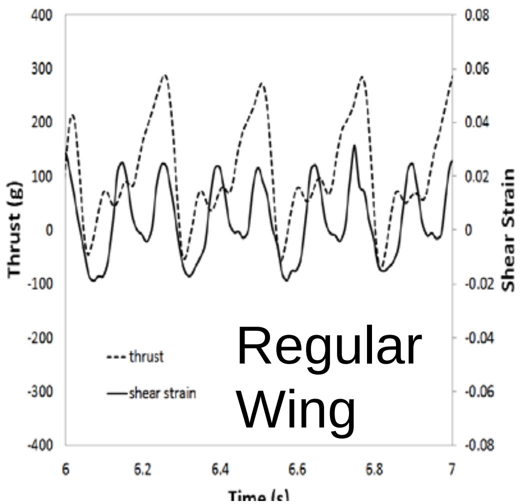
Digital Image Correlation

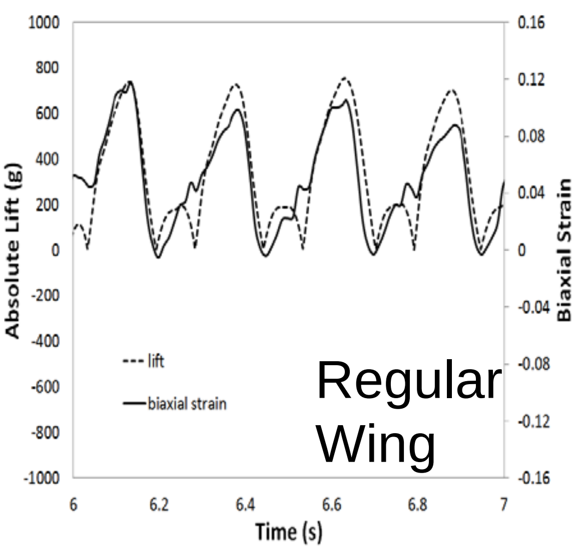
- The load cell results quantify the difference in force production of each wing; however, they do not tell us how the changes in the wing generate these different forces
- Digital Image Correlation (DIC) uses two cameras to record the speckled surface of the wing during flapping
- Using DIC software each frame is used to determine the deformation and strains on the surface of the wing

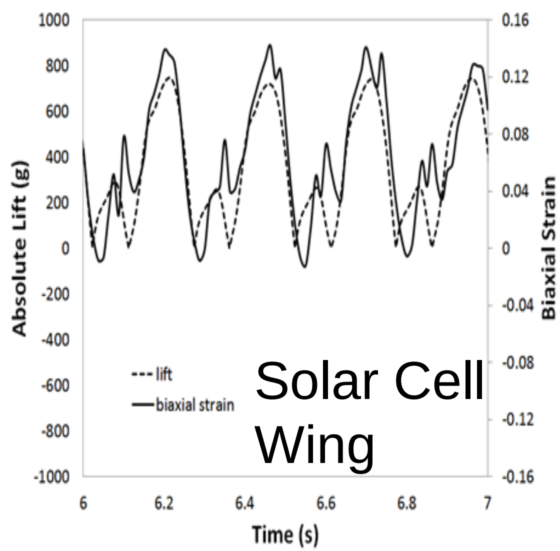


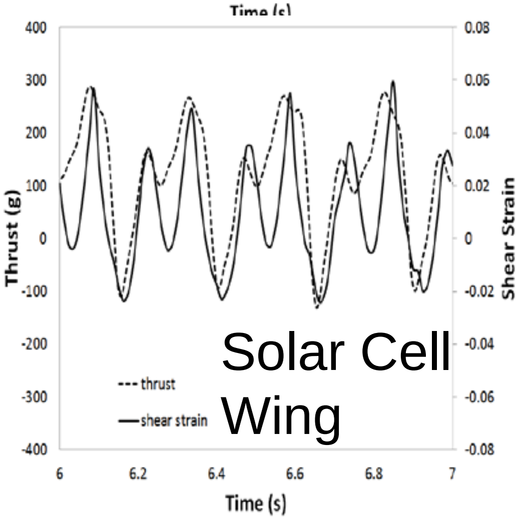
DIC Results

- DIC directly calculates the ε_{xx}, ε_{yy}, and ε_{xy} strains along the surface
- The biaxial strains ε_{xy} correlated well to the lift generated by the vehicle and the calculated shear strain correlated best to the thrust force generated by the vehicle



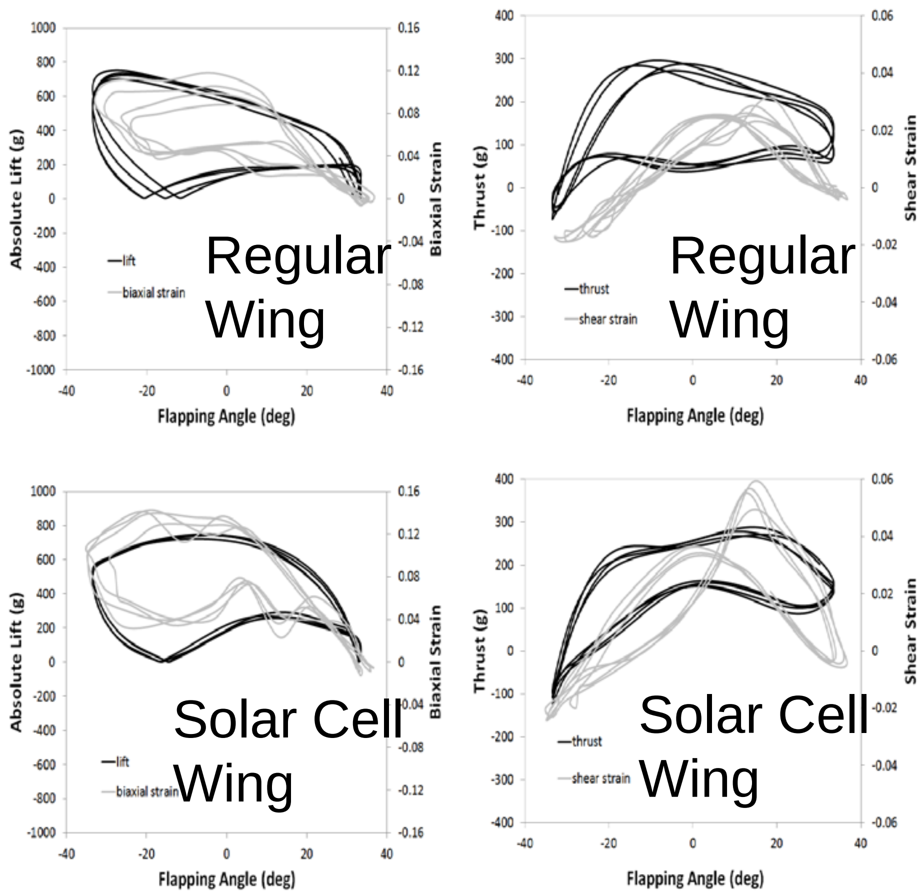






DIC Results (Cont.)

- To see just how well these data correlate to each other, they were plotted in relationship to wing position



DIC Results (Cont.)

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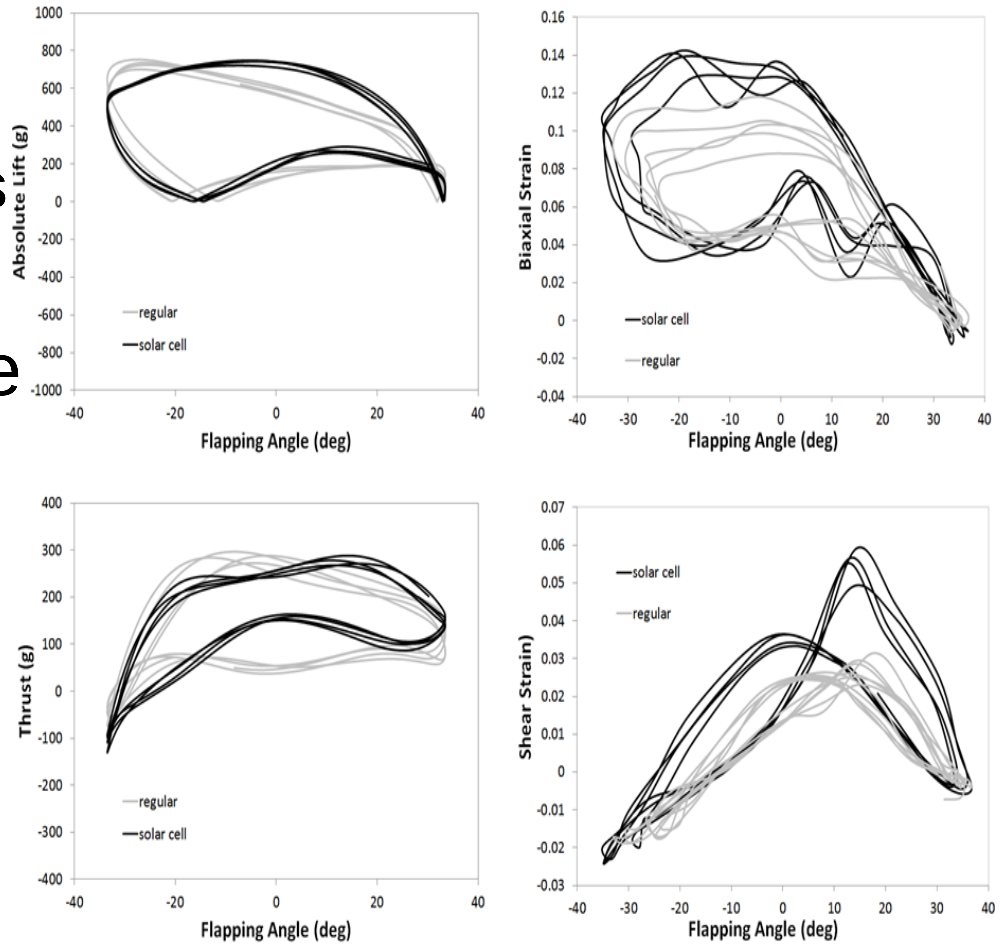
- Direct comparison of the wings
  - Left: Aerodynamic Forces
  - Right: Strains
- Solar cell wings generate higher forces and higher strains



Flight Testing Results

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Regular Wings		Solar Cell Wings	
Forward Velocity (m/s)	Climb Rate (m/s)	Forward Velocity (m/s)	Climb Rate (m/s)
5.75	0.6	5.75	0.32

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See Videos at

https://www.youtube.com/watch?v=t1_mPe8Y0V4

https://www.youtube.com/watch?v=a8x8P5F3qTI

Summary of Results

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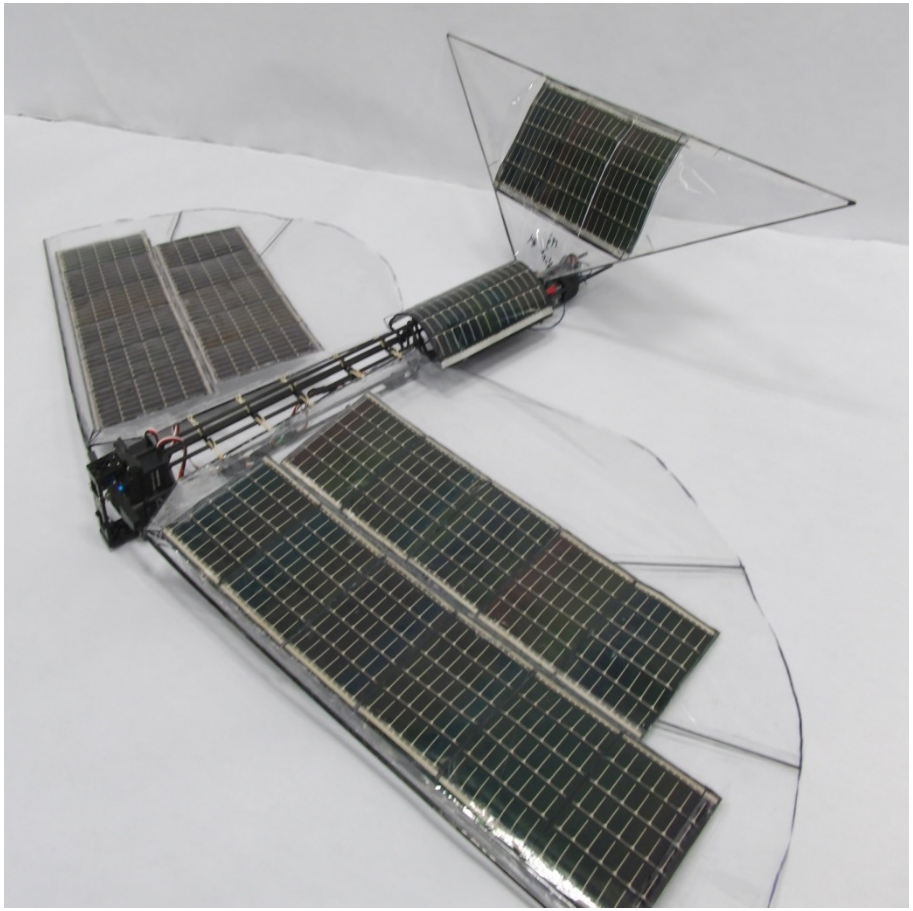
- The solar cells extend the flight time of the vehicle by 15.3% and charge the battery in 92 minutes
- DIC results show a correlation between residual thrust and shear strain and aerodynamic lift and biaxial strain
- A total of 20.2 grams were added to the vehicle due to solar cell integration but 11 grams were recovered by the change in wing design

New Design for Robo Raven III

- More solar cell coverage of the wings
- Multifunctional model of integrating solar cells to the wings
- More solar cell coverage throughout the body and tail
- Using more efficient solar cells
- Energy Harvested: 8.4W



Robo Raven IV

Robo Raven IV Goal

- Basic loitering control
  - Stabilization
  - Navigation
  - Data logging
- Stay within 40 gram payload

Robo Raven IV: Hardware Overview

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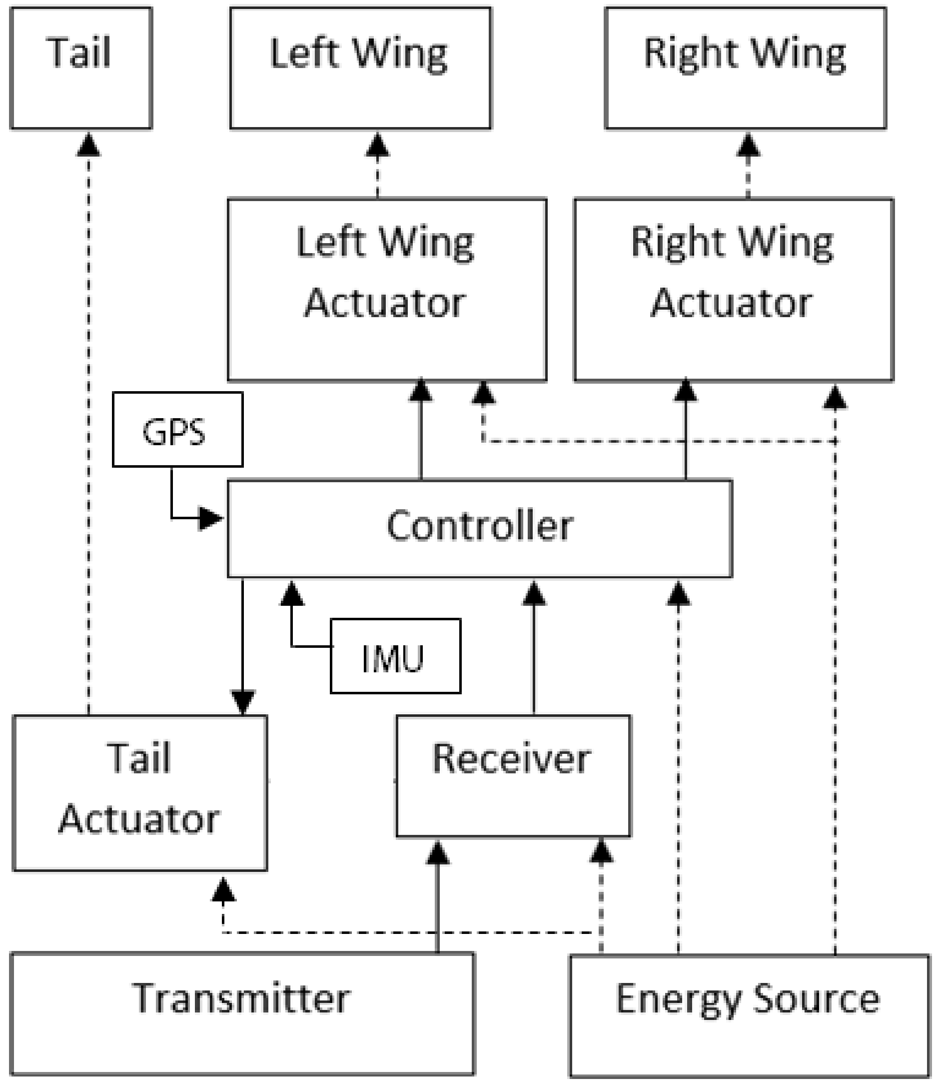
- ArduPilot Mega 2.5 Microcontroller
  - Accelerometer, gyroscope, compass
  - GPS/Xbee plugins
  - 16 MB DataFlash storage
  - 16 I/O pins
  - 28 grams
- Turnigy 7.4 V 370 mAh LiPo Battery
- Spektrum receiver
- Spektrum remote



Loitering: Topographical View

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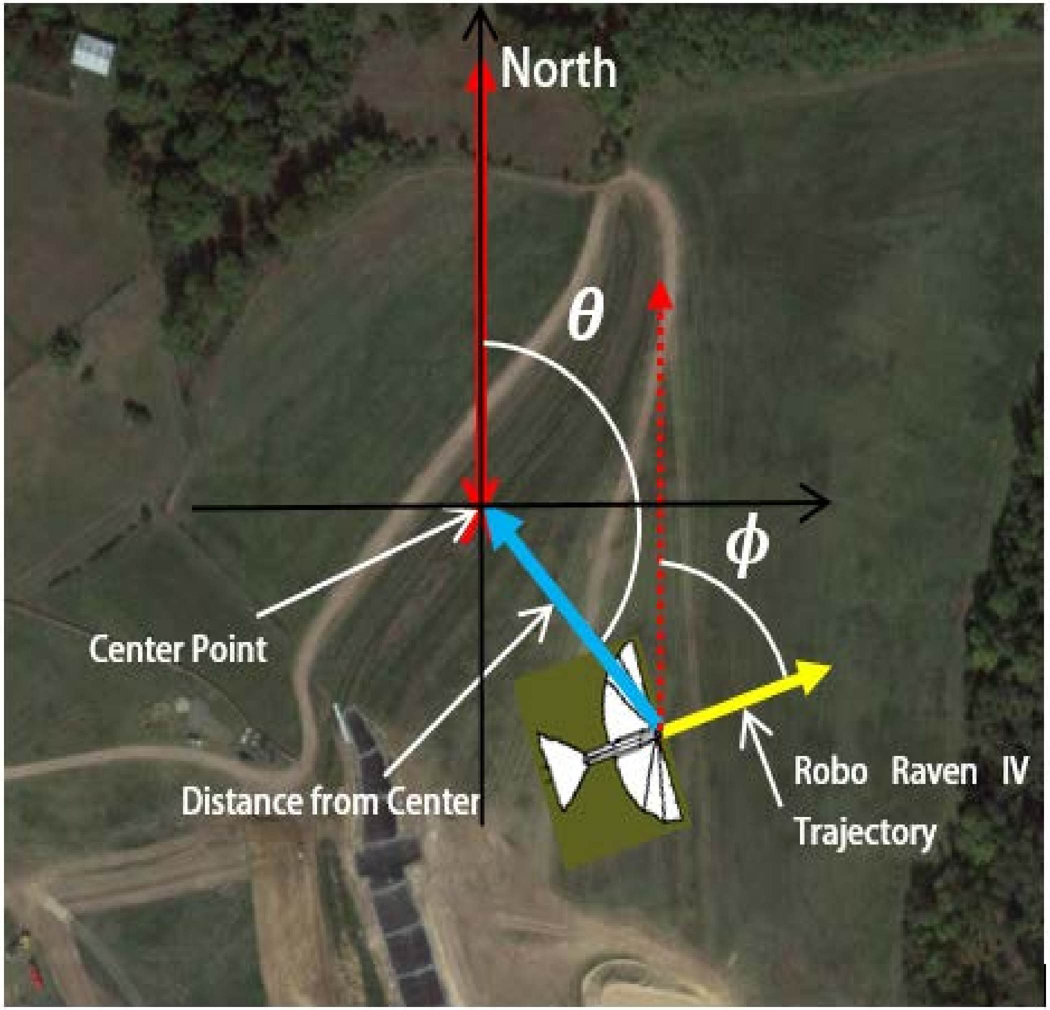
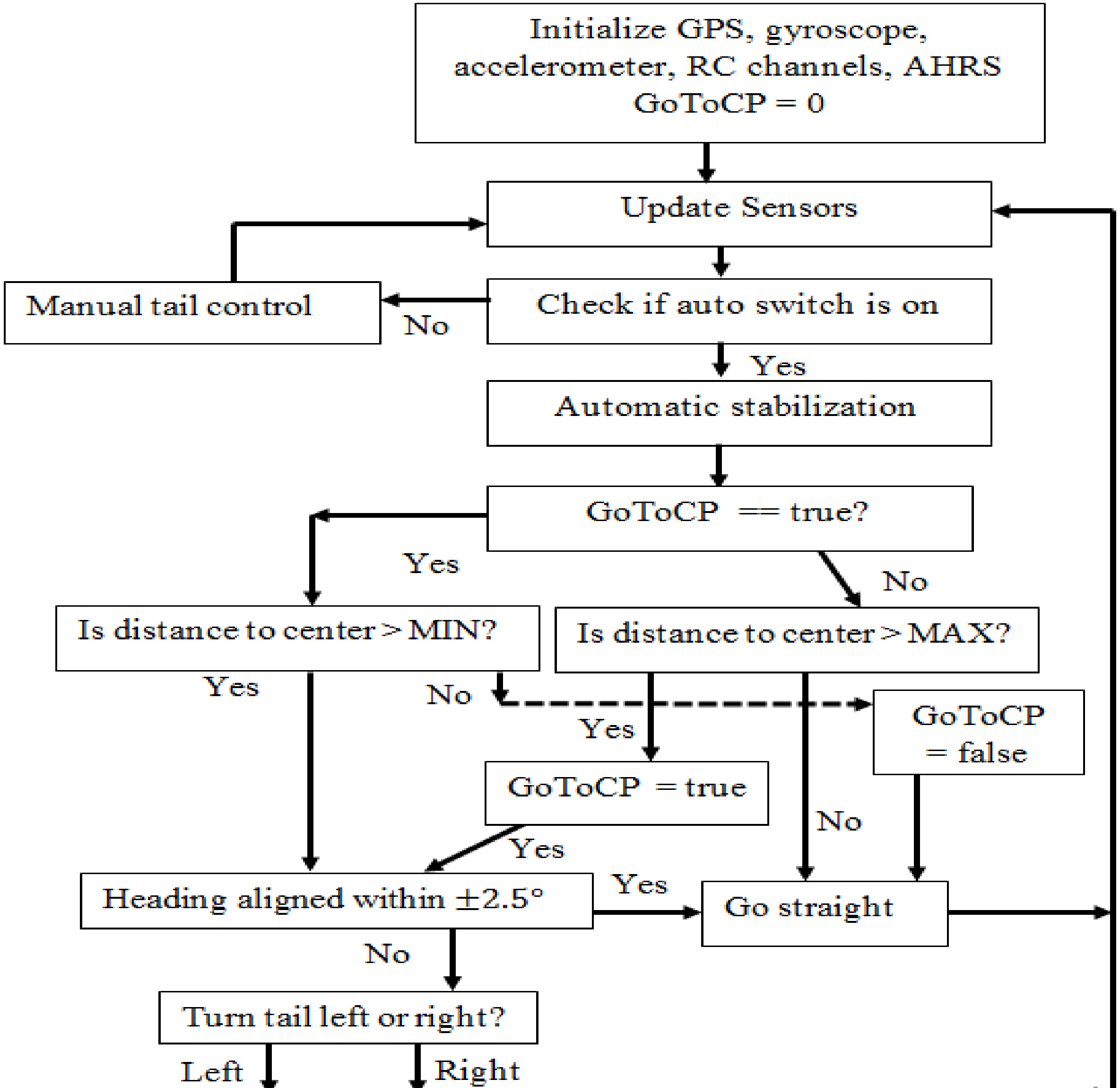


Loitering: Algorithm

- Navigation
  - GPS for localization
  - Compass for heading
  - Compare with desired position/heading
  - Set tail value to stabilize about to initiate turns to go to center point
  - Initiates when out of set range, stops when center point is reached (< 3 m)
- Stabilization
  - Tail as actuator controls roll/yaw
  - PID control

Loitering: Algorithm



Loitering: Error Characterization

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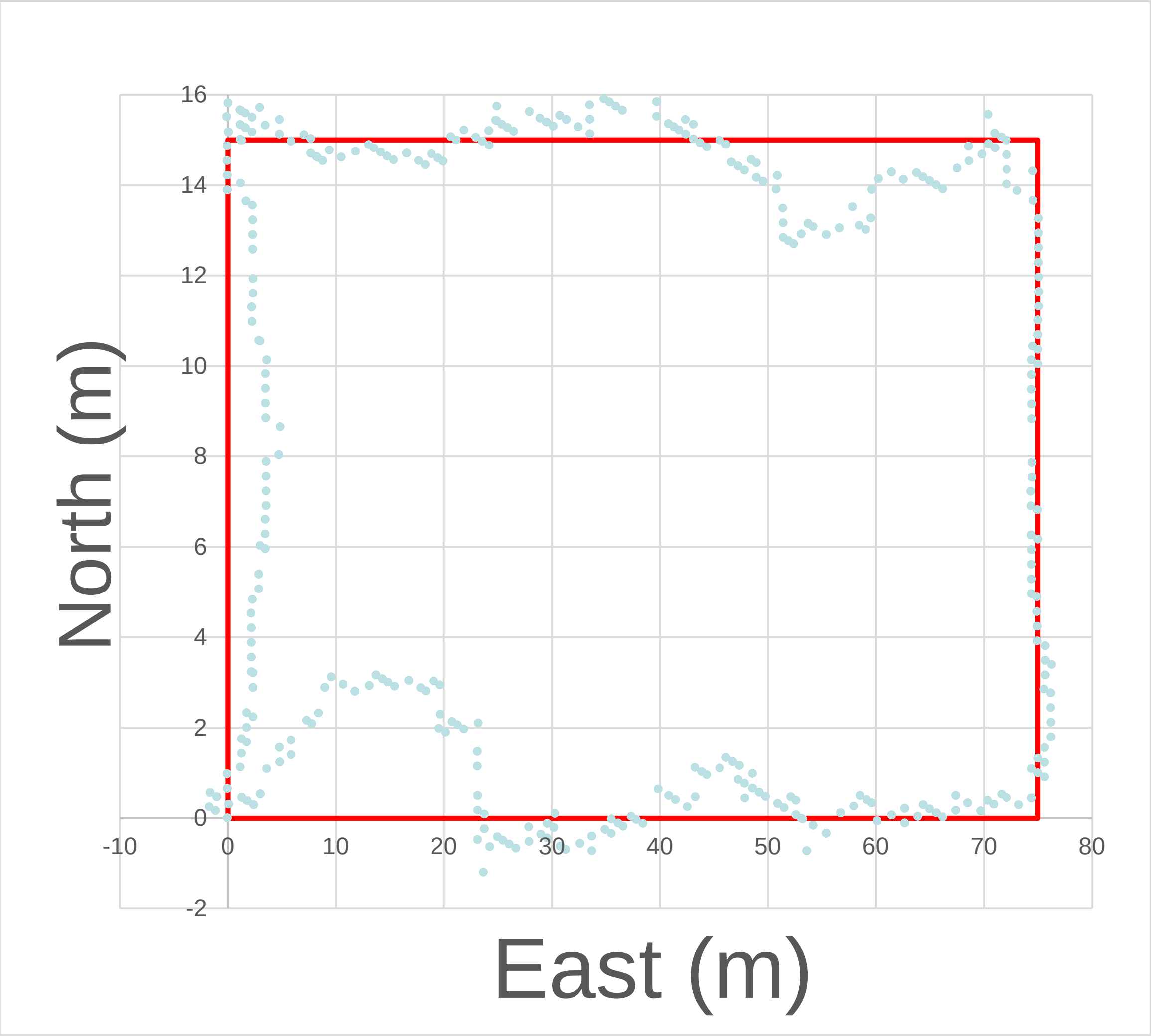
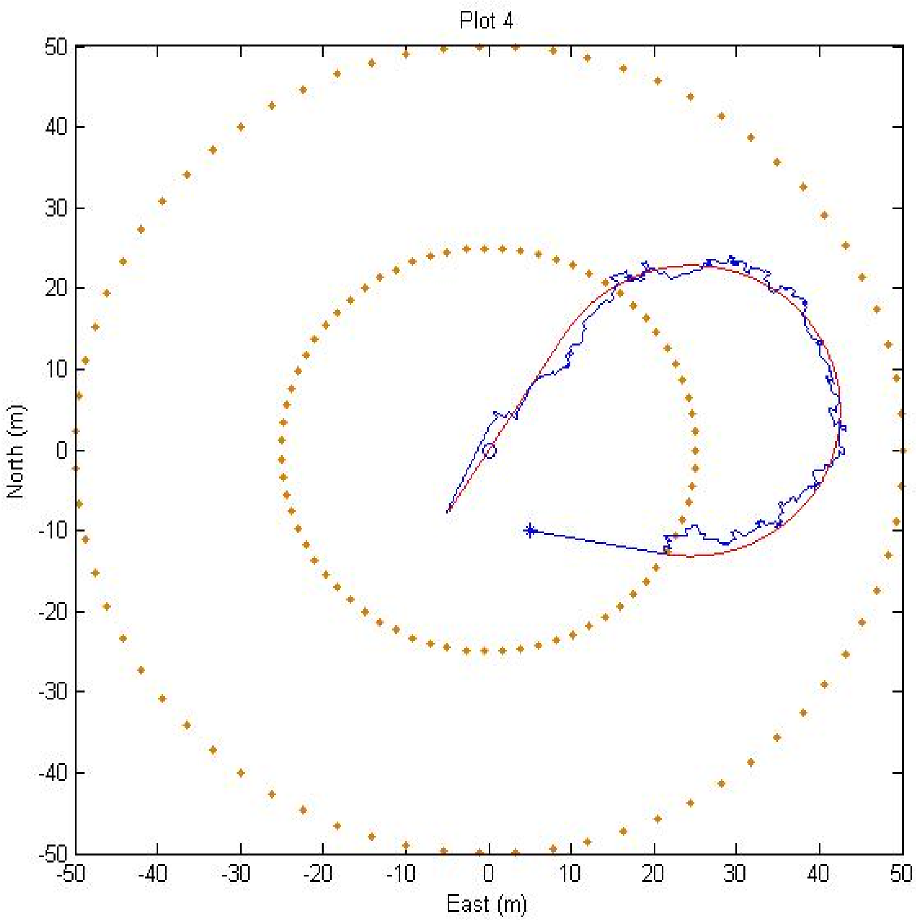
- GPS
  - Rectangle walk
  - Average error ~1m
  - Blue is GPS, red is path traveled



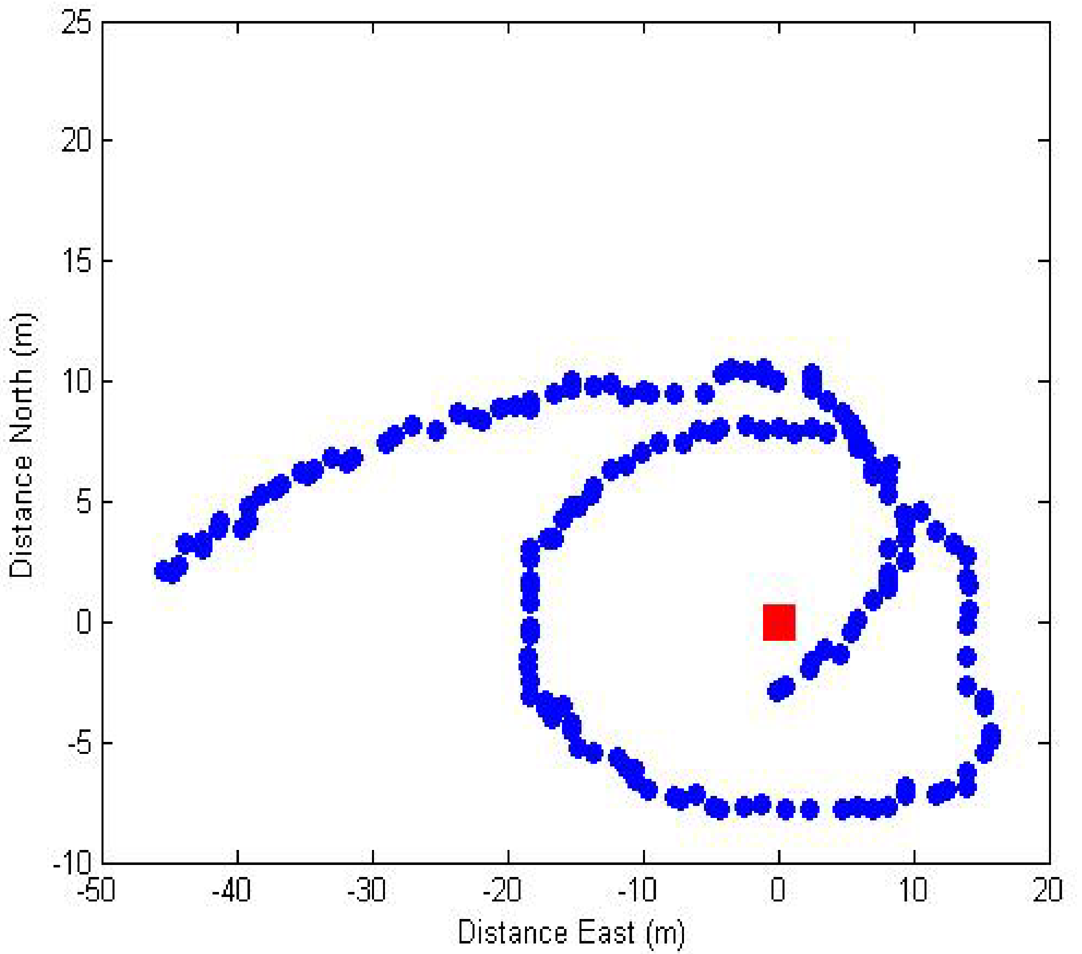
Simulation Results

- Matlab simulation with and without characterized error
  - GPS: add random value between σ and $-\sigma$ 4 times per second
  - Tail: Wait 150 ms once the turn is commanded before starting the turn
- Does not take wind into account



Flight Results: Log

- GPS log from Data Flash memory
  - Red dot is the center point
  - Blue is the bird position
  - Errors due to wind/GPS/tail error



See Video at
https://www.youtube.com/watch?v=nZ0sOFI5suw

Autonomous Dive

- Goal
  - Characterize and model dive maneuver of a FWAV to enable autonomous diving for chemical or visual inspection of an area without disturbing the environment
- Approach
  - Use Robo Raven IV platform (sensor suite, camera, autonomous stabilization and navigation)
  - Video FWAV dives at varying dihedral angles
  - Develop physics model by applying fixed wing gliding theory to the FWAV dive
  - Optimize lift and drag coefficients in model

Dive Characterization

Example of video dive data. Wings held at a 45 degree dihedral. Frames are 1/15 of a second apart.

Dive Characterization

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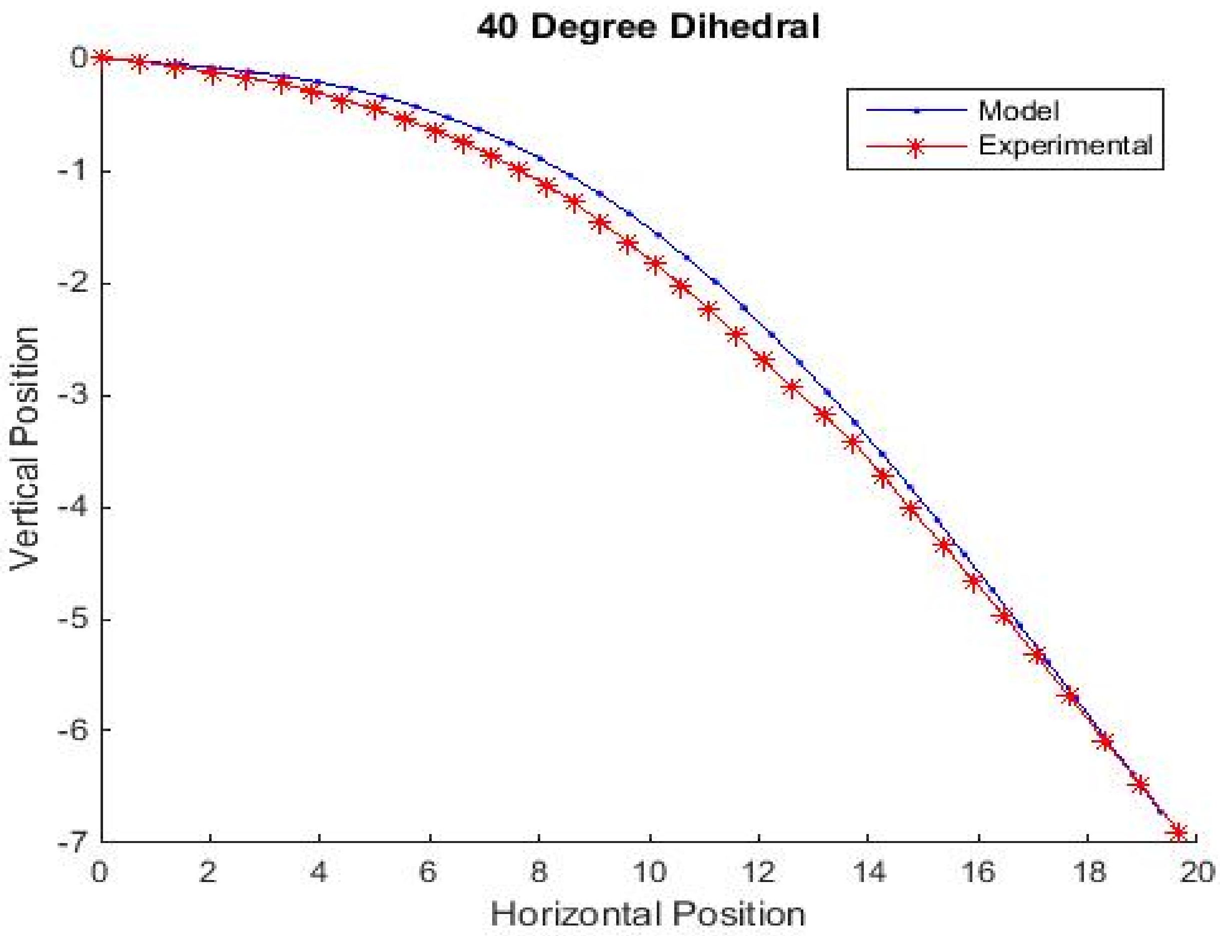

Future Directions

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- Complex autonomous behaviors
- Improved wing designs
- Mechanisms for autonomous launching, landing, and perching
- Soaring
- Improved sensing

Summary

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- Advances in robotics continue to improve manufacturing
- Realizing bio-inspired robots is challenging
  - Often requires new manufacturing approaches
  - We have developed unique capabilities to combine design, modeling & simulation, and manufacturing to realize novel robot concepts

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Questions?

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