Coordinated Robotics: from ideation, to prototype, to IP, to market

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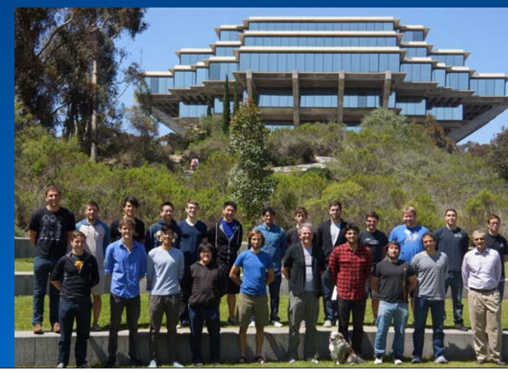
The UCSD Flow Control & Coordinated Robotics Labs

This work would not be possible without the amazing group of students that I'm fortunate enough to work with!



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UCSD Contextual Robotics, Summary Point #1

Robotic Systems are fundamentally interdisciplinary. TEAMWORK IS REQUIRED!!

Three main components:
SENSE, DECIDE, ACT

Sensing: EE-centric. 3D Vision/IR, microphone arrays, electronic nose.

Decision: CS- and CogSci-centric. SLAM/SFM. learning. finding "context".

Action: ME- or AE-centric. mobility, grasping. Agility facilitated by feedback control!

The modern theme that unifies these efforts:

collaborative / coordinated / cooperative / teaming. NSF: "co-robots"
(i.e., squads or swarms of bots working together & with people, directed autonomy)

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UCSD Contextual Robotics, Summary Point #2

Three main ingredients make robotics difficult:

DESIGN, TECHNOLOGY, ALGORITHMS

Design: Most visible to the public, most patentable.

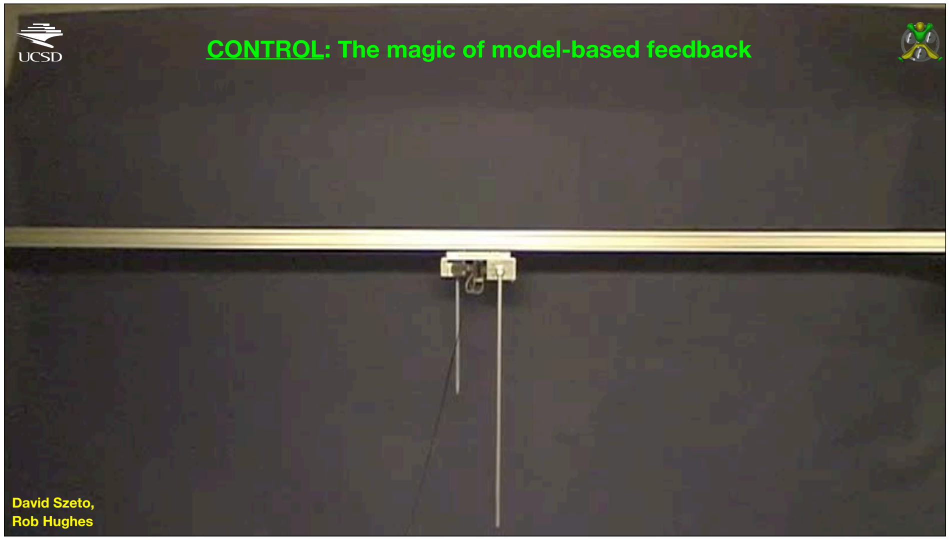
Technology: Constantly evolving, necessary to stay relevant.

Algorithms: Most "fundamental", most abstract.

Need all 3 to be effective. UCSD and its partners have unique strengths in all 3.

COMMERCIALIZATION keeps robotics in the public eye, creates broad impact.

EXPERIENTIAL EDUCATION in robotics needs to incorporate all three.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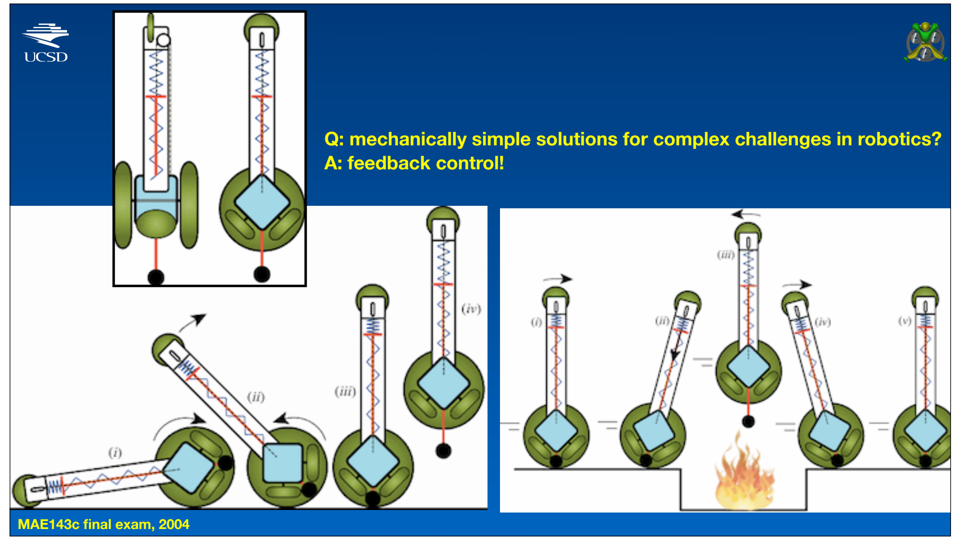
CONTROL: The magic of model-based feedback
David Szeto,
Rob Hughes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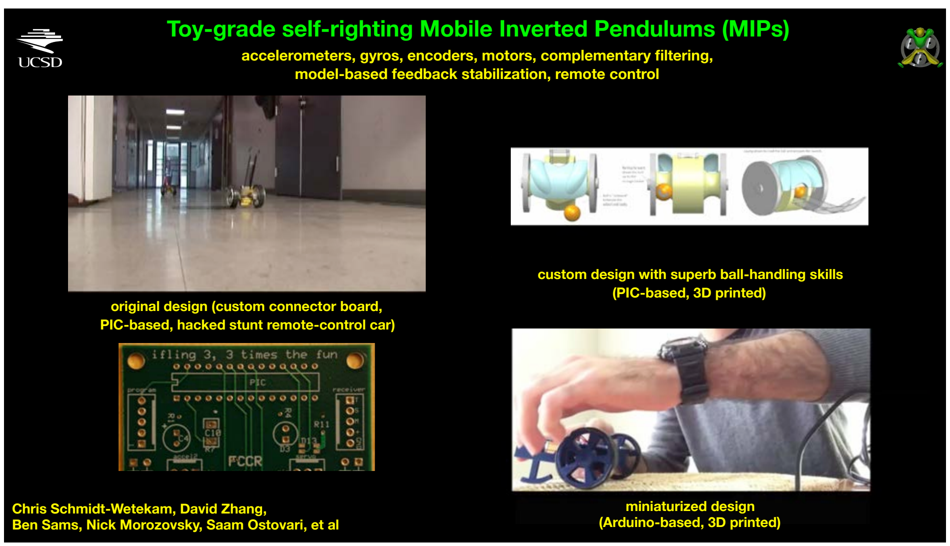
Q: mechanically simple solutions for complex challenges in robotics?
A: feedback control!
(i)
(ii)
(iii)
(iv)
(v)
MAE143c final exam, 2004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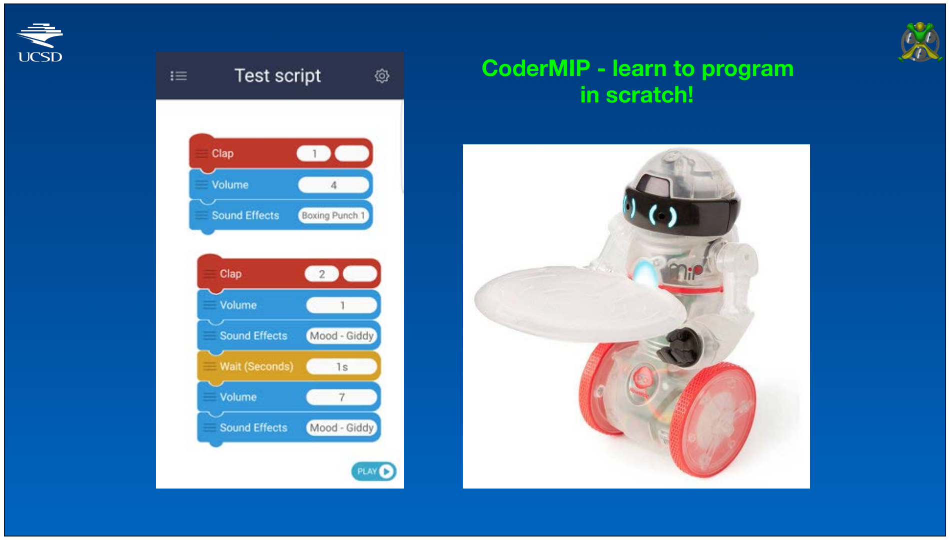
Toy-grade self-righting Mobile Inverted Pendulums (MIPs)
accelerometers, gyros, encoders, motors, complementary filtering,
model-based feedback stabilization, remote control
original design (custom connector board,
PIC-based, hacked stunt remote-control car)
custom design with superb ball-handling skills
(PIC-based, 3D printed)
miniaturized design
(Arduino-based, 3D printed)
Chris Schmidt-Wetekam, David Zhang,
Ben Sams, Nick Morozovsky, Saam Ostovari, et al


http://wowwee.com/mip
meet...
MiP™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Test script
Clap 1
Volume 4
Sound Effects Boxing Punch 1
Clap 2
Volume 1
Sound Effects Mood - Giddy
Wait (Seconds) 1s
Volume 7
Sound Effects Mood - Giddy
PLAY
CoderMIP - learn to program
in scratch!


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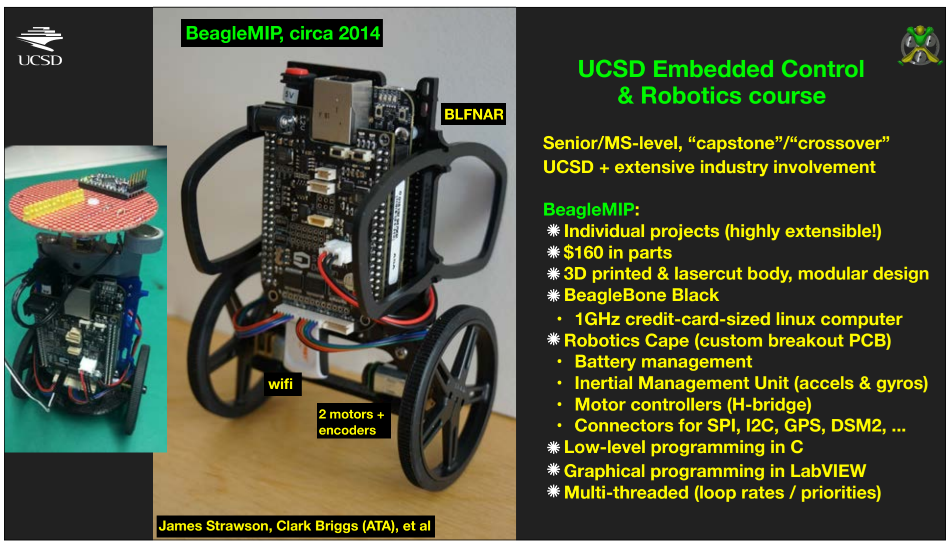
Let passions feed
knowledge, and
students flourish.
"The greatest sign of success for a teacher... is to be able to say,
'The children are now working as if I did not exist.'"
–Dr. Maria Montessori
Imagine your tween or teen eager to go to school, and excited to
learn in a supportive, mixed-age community of motivated peers.
Imagine her developing essential executive function skills—time
management, organization, and cooperation.
LePort
MONTESSORI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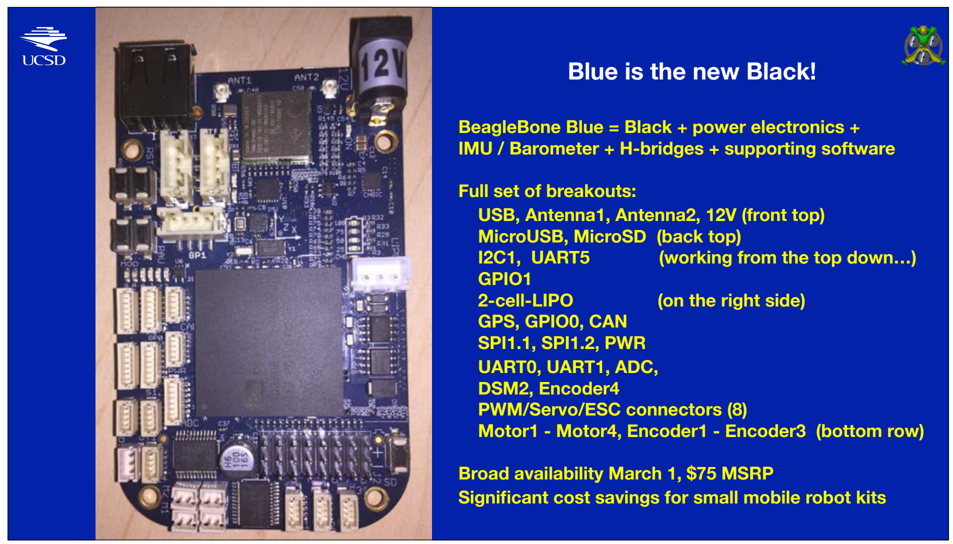
BeagleMIP, circa 2014
BLFNAR
wifi
2 motors +
encoders
James Strawson, Clark Briggs (ATA), et al
UCSD Embedded Control
& Robotics course
Senior/MS-level, "capstone"/"crossover"
UCSD + extensive industry involvement
BeagleMIP:
Individual projects (highly extensible!)
$160 in parts
3D printed & lasercut body, modular design
BeagleBone Black
1GHz credit-card-sized linux computer
Robotics Cape (custom breakout PCB)
Battery management
Inertial Management Unit (accels & gyros)
Motor controllers (H-bridge)
Connectors for SPI, I2C, GPS, DSM2, ...
Low-level programming in C
Graphical programming in LabVIEW
Multi-threaded (loop rates / priorities)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12V
Blue is the new Black!
BeagleBone Blue = Black + power electronics +
IMU / Barometer + H-bridges + supporting software
Full set of breakouts:
USB, Antenna1, Antenna2, 12V (front top)
MicroUSB, MicroSD (back top)
I2C1, UART5 (working from the top down...)
GPIO1
2-cell-LIPO (on the right side)
GPS, GPIO0, CAN
SPI1.1, SPI1.2, PWR
UART0, UART1, ADC,
DSM2, Encoder4
PWM/Servo/ESC connectors (8)
Motor1 - Motor4, Encoder1 - Encoder3 (bottom row)
Broad availability March 1, $75 MSRP
Significant cost savings for small mobile robot kits

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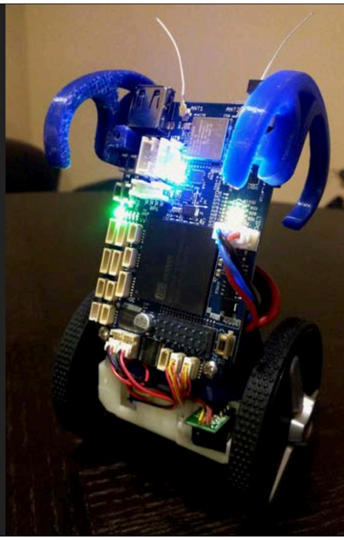

eduMIP

BeagleBone Blue is all-in-one solution for small robots.

All ports fully tested and supported via a thread-safe C library in Debian linux, with working examples.

LabVIEW and Matlab wrappers under development.

- 2-cell LiPo (power up on board through 12V charger)
- plugs for I2C, SPI, UART, CAN, GPIO, DSM2, GPS, ADC
- H-bridges for 4 bidirectional motors
- 4 encoder counters
- 8 PWM outputs for Servos and ESCs

Get started in multithreaded robotics quickly!

Significant cost savings compared with multiple-board solutions (e.g., Black + Capes)

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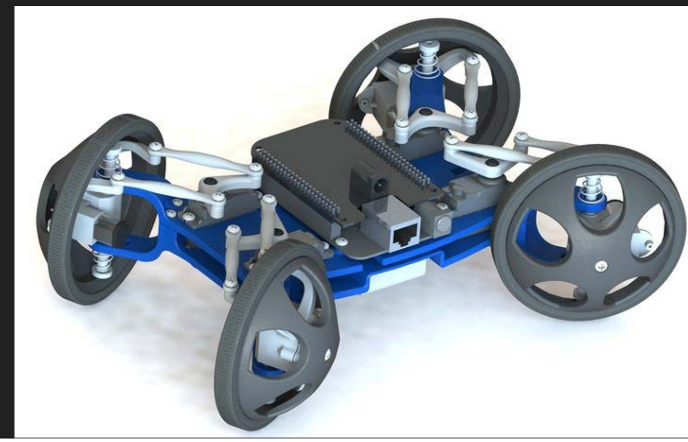
eduRover: 4WD, extreme 4-wheel steering. Same electronics, same software library.



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eduMAV: Optimization of angles for direct side force (w/o banking!) Same electronics, same software library.

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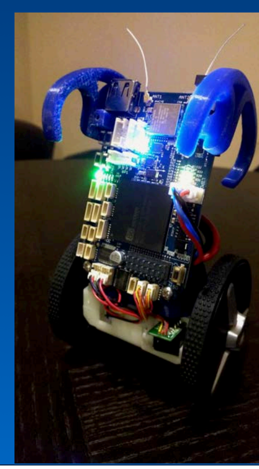
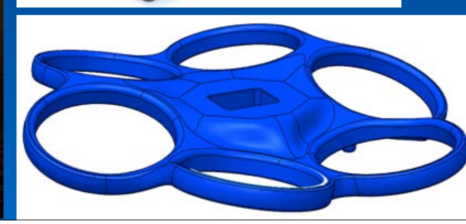
eduMIP, eduRover, eduMAV: three low-cost robotic systems, shared hardware and software library





Renaissance Robotics

agile design, coördinated response,
& multithreaded behavior

Part I. Inception

1 Interconnecting the cyber & physical worlds
2 Software environments & operating systems
3 Digital circuits & communication architectures
4 3D mechanical design & fabrication
5 Electrical design & fabrication

Part II. Foundation

6 Kinematics & dynamics
7 Signals & systems: transform-based methods
8 Classical control design
9 Linear Circuits
10 Multithreaded software development using embedded Linux and C

Part III. Hands-on

11 Getting started with the Beaglebone Blue
12 eduMIP: an extensible mobile inverted pendulum
13 eduRover: an agile 4WD/4WS vehicle
14 eduMAV: a micro air vehicle for stable aerial videography

Part IV. Flourish

15 Agile Vehicle Design Inspirations
16 Situational awareness
17 Path planning & collision avoidance
18 Adaptive observation & forecasting
19 Underactuated (buoyancy) control in stratified flow systems

Supplement

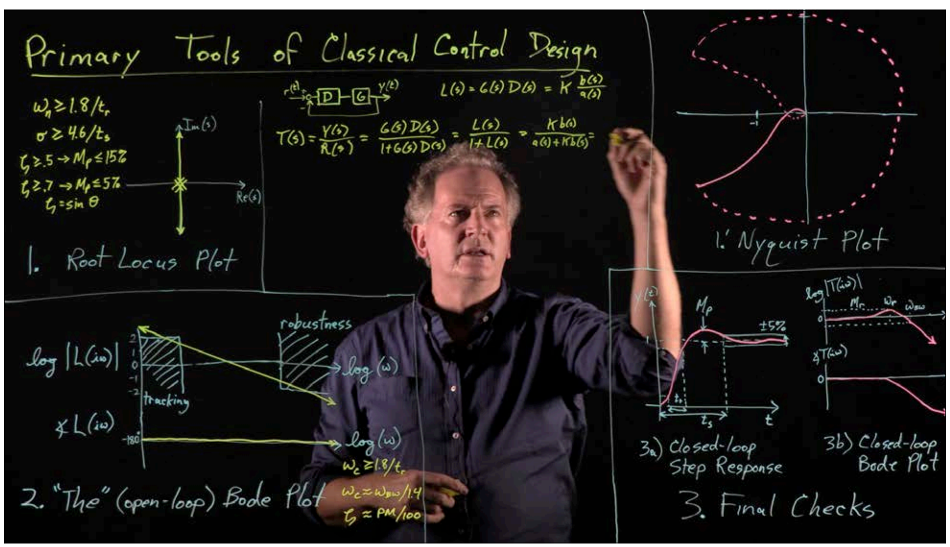
A A brief introduction to programming
B Assorted mathematical foundations

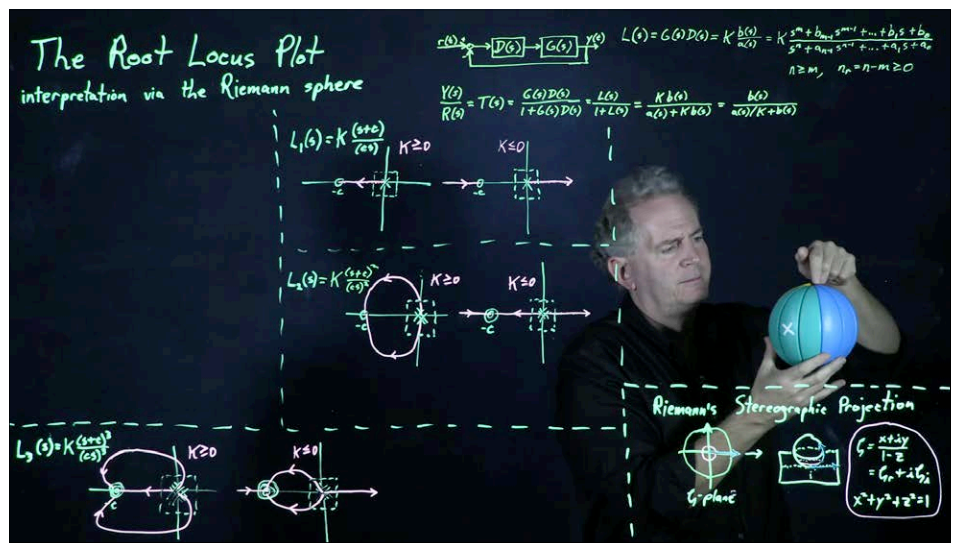
Chapter 10

Signals & systems: transform-based methods

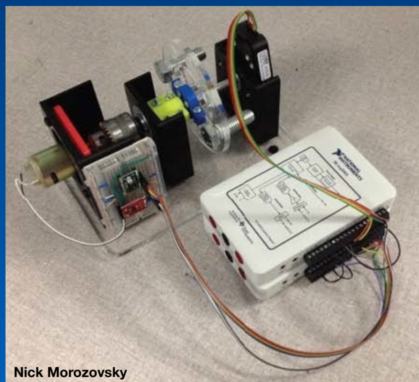
Contents

10.1 Introduction to transforms: Fourier, Laplace, and Z
10.1.1 The relation of the Laplace and Z transforms to the Fourier transform
10.1.2 The remarkable utility of such transforms
10.2 Laplace transform methods
10.2.1 The Laplace Transform of derivatives and integrals of functions
10.2.2 Using the Laplace Transform to solve unforced linear differential equations
10.2.3 Continuous-time (CT) transfer functions
10.2.3.1 Proper, strictly proper, and improper CT systems
10.3 Z transform methods
10.3.1 The Z Transform of translated sequences
10.3.2 Using the Z Transform to solve unforced linear difference equations
10.3.3 Discrete-time (DT) transfer functions
10.3.3.1 The transfer function of a DAC – $G(s)$ – ADC cascade
10.3.3.2 Causal, strictly causal, and noncausal DT systems
10.3.4 Reconciling the Laplace and Z transforms
10.3.4.1 Tustin's approximation
10.3.4.2 Tustin's approximation with prewarping
10.4 Frequency-domain analyses and filters
10.4.1 The Bode plot
10.4.1.1 Sketching Bode plots of real systems by hand
10.4.2 Low-pass, high-pass, band-pass, and band-stop filters
10.4.2.1 Maximal flatness filters: Butterworth and Bessel
10.4.2.2 Equiripple filters: Chebyshev, inverse Chebyshev, and elliptic†
Exercises

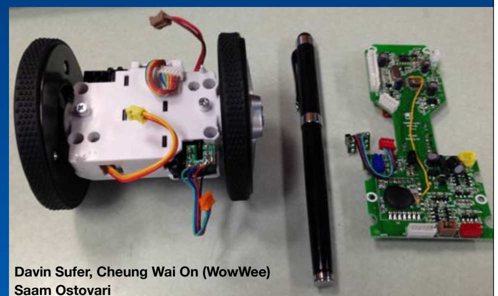




Design for low-cost manufacturing



Nick Morozovsky



Davin Sufer, Cheung Wai On (WowWee)
Saam Ostovari

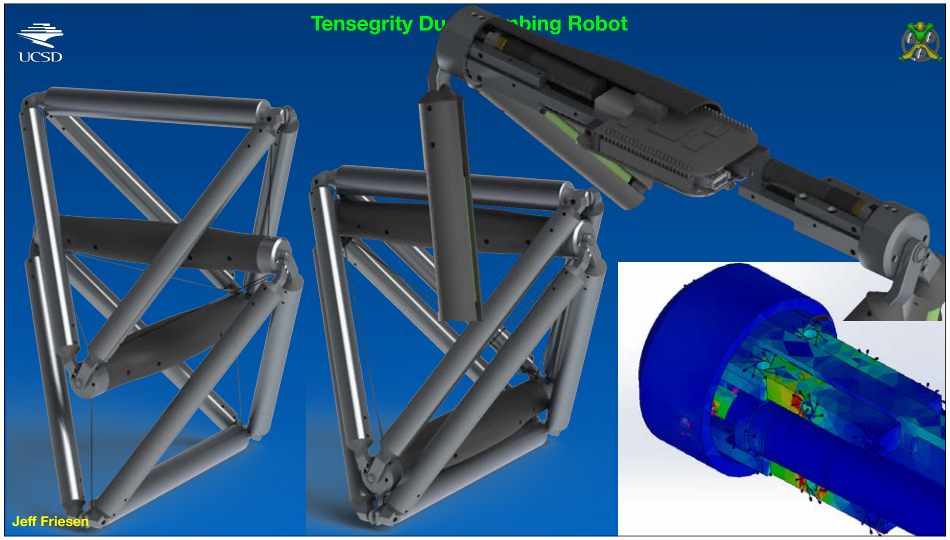
Robust, manufacturable internals

Maximize use of “pick and place” machines.
Survive the demanding requirements of a 2 year old.

Small Motor Dynamometer

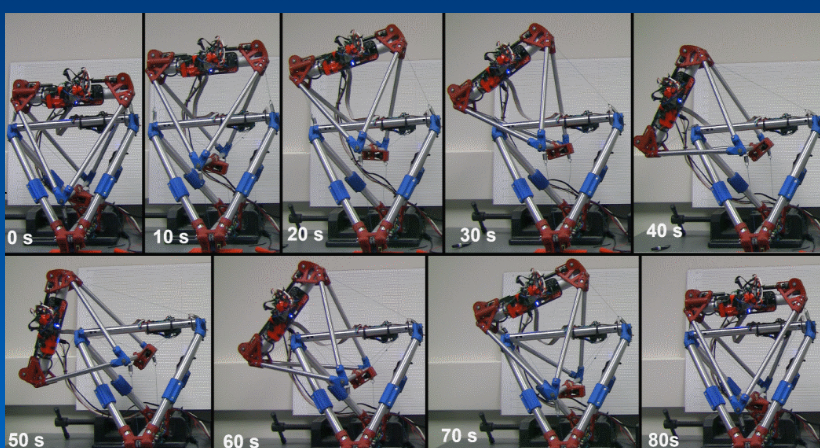
Required to model motor driver + motor + gearbox combinations for control feedback. *Now open source!*

Tensegrity Du… bing Robot



Jeff Friesen

Tensegrity Duct-Climbing Robot



Jeff Friesen

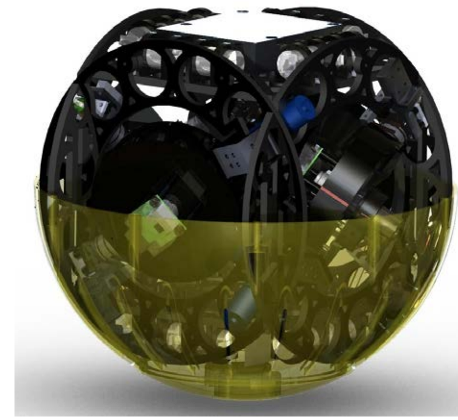
Tensegrity Duct-Climbing Robot

Jeff Friesen

IceCube (patent pending)

Andrew Cavender

IceCube (patent pending)



Andrew Cavender

Competing spherebot design

GuardBot, Inc

WHY? Applications motivating low-cost robotic systems

1. Inspirational toys and educational robotics projects
2. Elder care: companionship & monitoring of old folks in their homes
   - postpone being sent to managed care facilities, which is expensive
3. Assistance to the handicapped (wheelchairs that can climb stairs, prosthetics, …)
4. Water filtration systems
5. First responders (firefighters, police, …)
   - provide fast situation awareness and communication without getting in harm’s way.
6. Security / patrol
7. Farming: precise delivery of water, pesticide, & fertilizer to each plant. Harvesting.
8. Forecasting of contaminant plumes in the environment
9. Forecasting hurricanes and typhoons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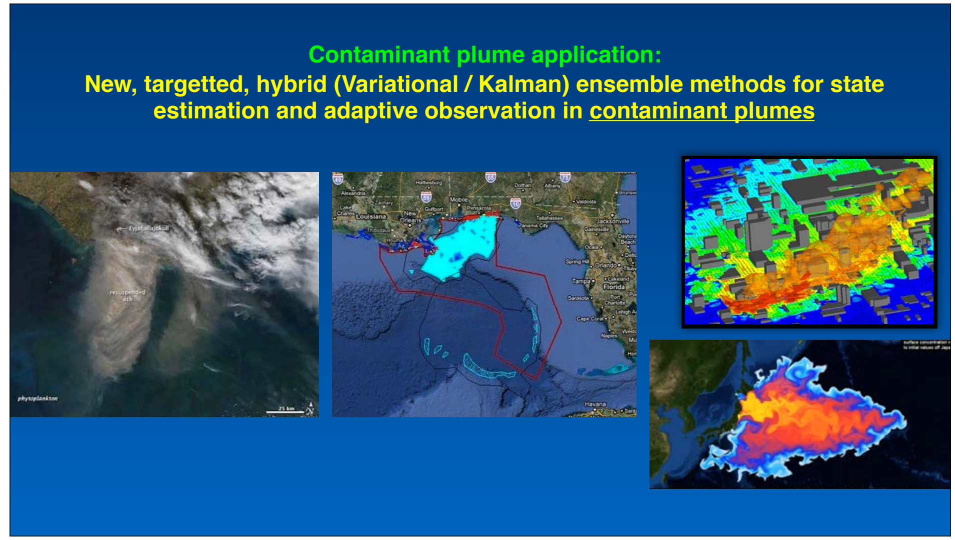
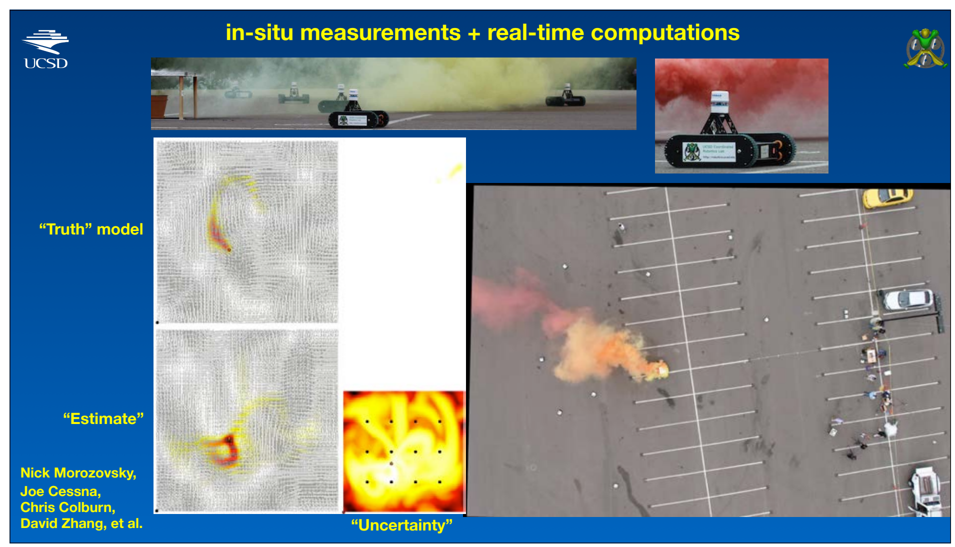
Finding Context: Simultaneous Localization & Mapping (SLAM)
Structure from Motion (SfM)
Rogue
Google Project Tango
Occipital Structure Sensor
Daniel Yang et al
Thermal mapping onto 3D VRs using robustified UCSD MIPs
Qualcomm FastCV/Vuforia


Contaminant plume application:
New, targetted, hybrid (Variational / Kalman) ensemble methods for state estimation and adaptive observation in contaminant plumes


parking-lot scale
experiments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in-situ measurements + real-time computations
"Truth" model
"Estimate"
"Uncertainty"
Nick Morozovsky,
Joe Cessna,
Chris Colburn,
David Zhang, et al.

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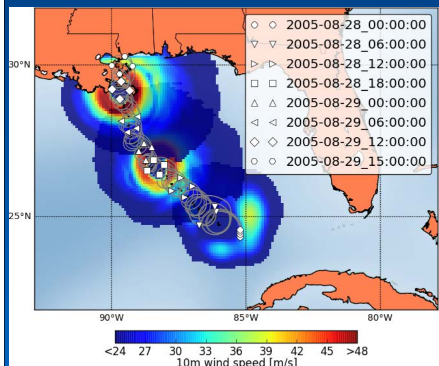
Application to hurricanes and typhoons:
Efficient coordination of swarms of sensor-laden balloons for persistent, in situ, real-time measurement of hurricane development



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A) Gigascale computing at 1 watt for robotic sensor vehicles.

Cray-2
(c. 1985-1990)
1.9 GFLOPS
824 DMIPS
200 kW

Snapdragon
Flight (2015)
~10^4 DMIPS
10 x Cray-2
1 W

(2013)
Ridge)
PFLOPS
Cray-2
MW

C) Thousands of the worlds top scientists focusing on environmental fluid dynamics.

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A) Gigascale computing at 1 watt for robotic sensor vehicles.

B) Petascale computing: Moore's dream, realized.

C) Thousands of the worlds top scientists focusing on environmental fluid dynamics.

D) Global Internet Access

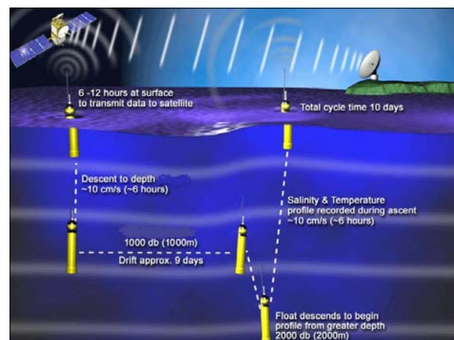
Available Geosynchronous (36,000 km altitude) satellites:
Inmarsat (1979), MSAT, Terrestar, ICO
Available LEO (1200-1400 km altitude) constellations:
Globalstar (1999, 40 satellites)
Iridium (1998/2001, 66 satellites)
Argos DCS (1978, 6 polar-orbiting satellites)

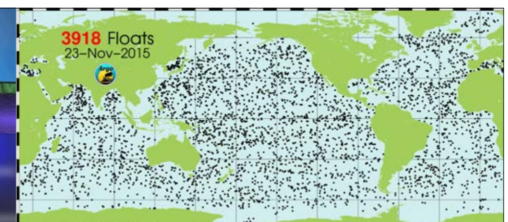
...t a confluence of powerful capabilities.
They present opportunities for fundamental improvements in our ability to measure and forecast significant environmental flows on our planet.

Iridium satellites

Forthcoming solutions (availability within 5 years?):
OneWeb (Qualcomm, Greg Wyler, Richard Branson; 600 LEO satellites)
SpaceX (Google, Fidelity, Elon Musk; 4,000 LEO satellites)
Project Loon (Google; thousands of balloons at 18 km = 60,000 feet)

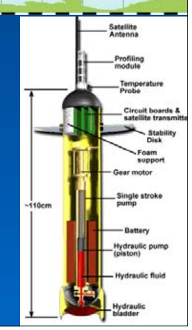
The purpose of this segment is to discuss these opportunities.





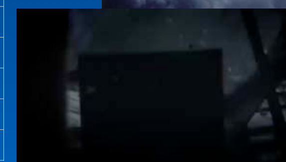
ARGO: an existing global flow observation system

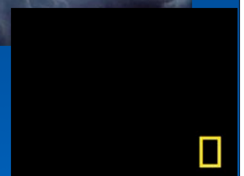
Argo is a global array of ~4000 free-drifting profiling floats that continuously monitor temperature, salinity and velocity of the upper 2km of the ocean.
All data is relayed and made publicly available within hours after collection.



Hurricanes are costly and deadly

Hurricane	Year	Cost	Fatalities
Sandy	2012	$71B	286
Irene	2011	$17B	56
Ike	2008	$38B	195
Katrina	2005	$125B	1833
Wilma	2005	$29B	23
Rita	2005	$12B	62
Jeanne	2004	$7B	3035
Ivan	2004	$23B	124
Charley	2004	$15B	40
Mitch	1998	$6B	19325
Andrew	1992	$27B	65

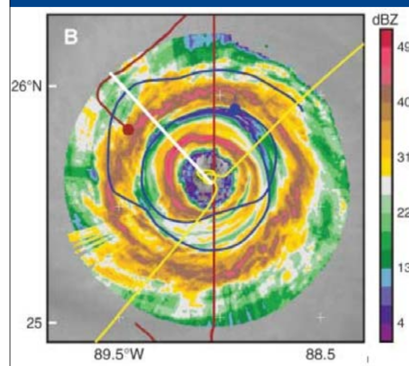


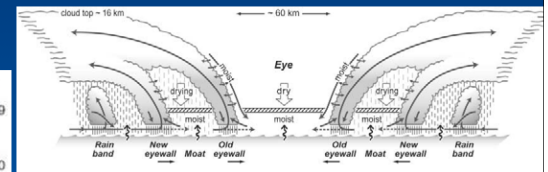


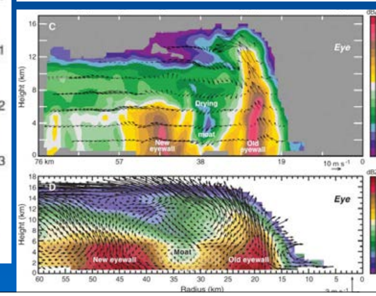
Extensive real-time in situ measurements are essential for supplementing satellite info to improve 2-5 day forecasts of hurricane tracks and intensities

Observation of hurricanes via fly-overs and dropsondes is difficult. Further, the physics of large hurricanes is sometimes complicated.

Flight paths over Hurricane Rita



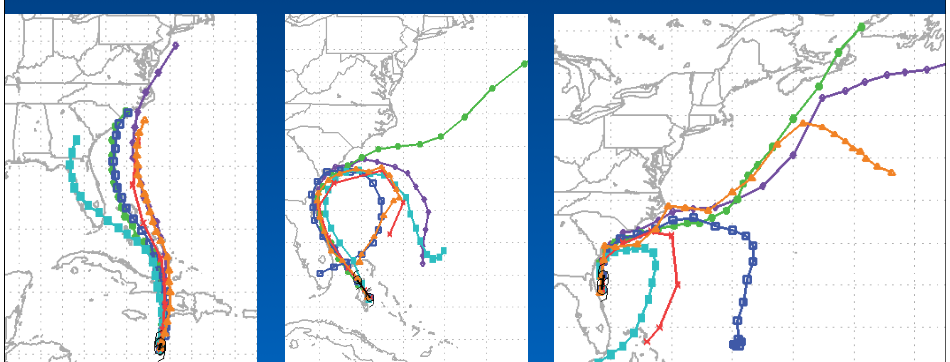




In Rita, an old eyewall diminished, and a new one merged with it. (Houze et al., Science 2007)

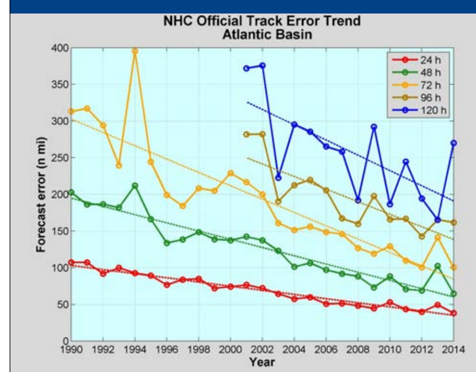
Forecasting Hurricanes is difficult!

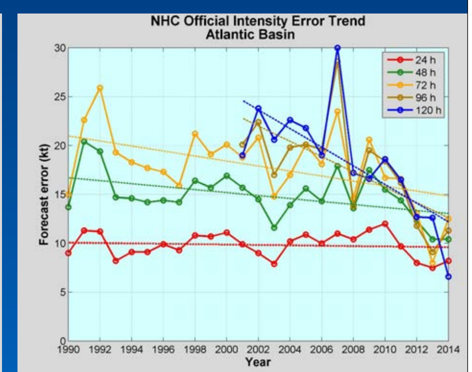
Forecasts of Hurricane Matthew, as performed by the major hurricane forecasting centers on (left) Oct 3, (middle) Oct 6, and (right) Oct 7, 2016



Hurricane forecast improvements over the last 25 years

(Cangialosi & Franklin 2015)

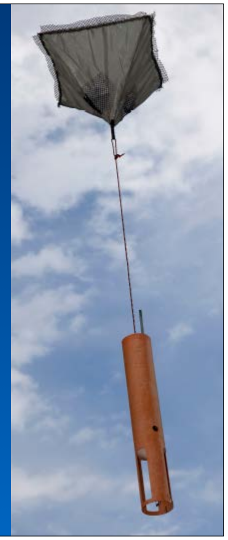




The importance of in situ measurements

(Wang, Young, Hock et al, *BAMS,* June 2015)

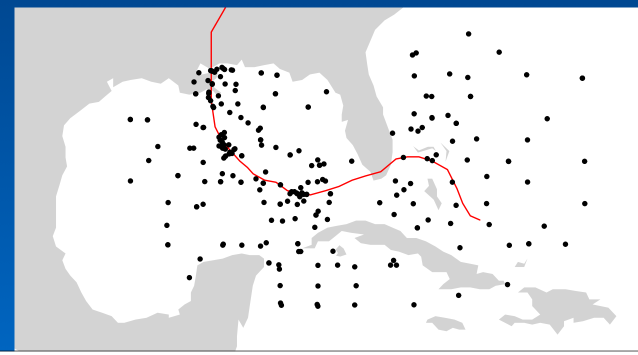
"**Since 1996, GPS dropsondes have been routinely deployed** during hurricane reconnaissance and surveillance flights… During the first season of NOAA Gulfstream-IV missions for hurricanes in 1997, 150 dropsondes were released from aircraft at 150–200-km intervals… This first set of dropsonde observations **improved mean hurricane-track forecasts by 32% and intensity forecasts by 20% during the critical first two days of the forecast**. The track forecast improvements were comparable to those accumulated over the past 20–25 years at that time. Mean track forecast improvement as a result of synoptic surveillance dropsondes during 1999–2005 is … above 10% during 0–48 h."



Observation of Katrina with dropsondes

(data from Wang, Young, Hock et al, *BAMS,* June 2015)

In Katrina (2005), one of the most carefully measured hurricanes ever, only 286 dropsondes were used (total), dropped from ~14km (Gulfstreams) and ~3km (P-3D Orions). Each dropsonde takes 100 to 1000 measurements.



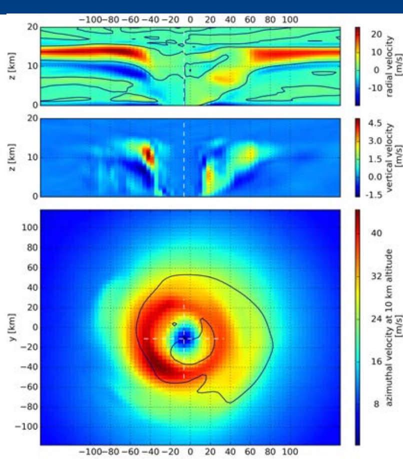
Idea: Underactuated control of sensor balloon distribution in hurricanes

inflow at lower altitude

updraft within the eyewall

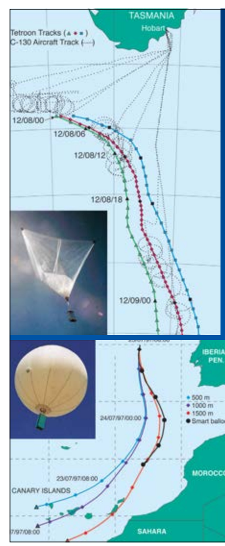
outflow at higher altitude (up to 15km)

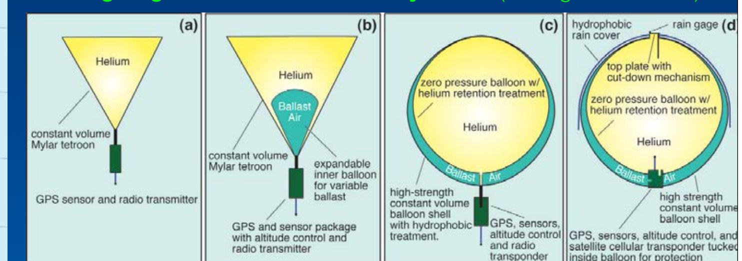
azimuthal velocity changes with radius

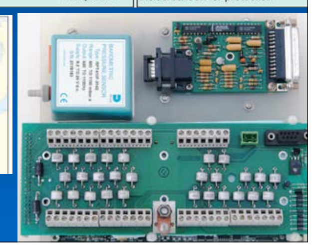


Balloons act as Lagrangian tracers in x and y. Controllable in z.

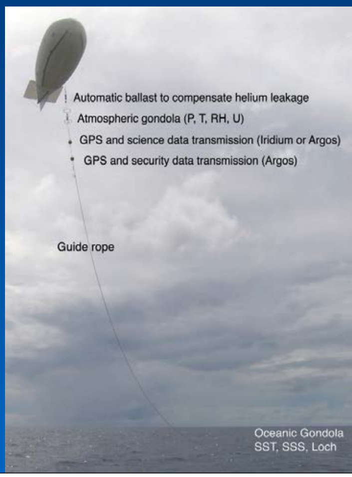
Lagrangian "Smart" Balloons by NOAA (Businger et al 2006)

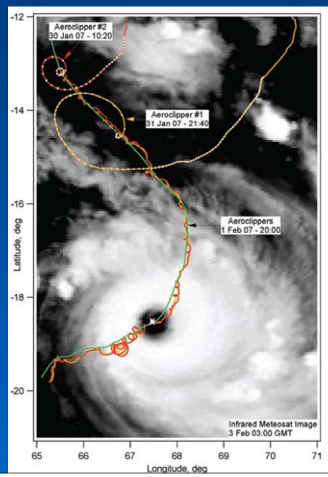






Low-altitude blimp observations by the Aeroclipper (Duvel et al, 2009)





Altitude-cycling balloons designed for Venus, Titan (Thin Red Line, 2015)

space-certified, stowable, self-inflating balloons

Altitude-cycling balloon design capable of 3x volume change

To reduce condensation: 1. Coat with Teflon (hydrophobic). 2. Construct fillets between segments. Also, squeezing balloon (for altitude control) tends to flake off ice that forms.

Key challenges for balloon flights in hurricanes

Aircraft deployment (self inflation upon release)

Neutrally bouyant between 1km and 8km altitude (~2.2x change in density altitude)

Control (slowly) the vertical velocity up to +/- 2m/s. Use a winch (motor) inside to drive a cable.

Sensors: temperature, pressure, humidity, GPS

Radios: communicate with LEO, or use ad-hoc mesh network to relay messages. Very low data rate.

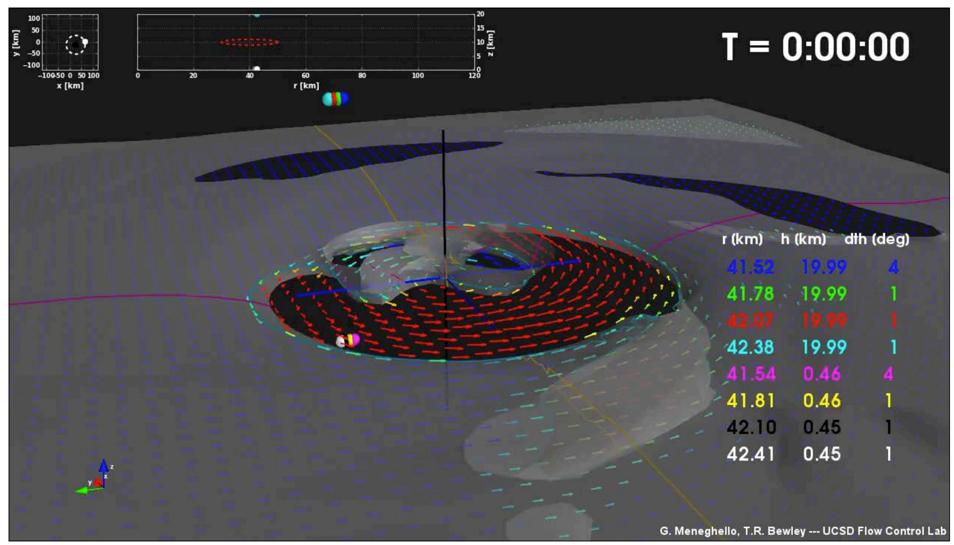
Cold lithium battery operation for up to 5 days. Chemistry: Li-SOCl2 (rated to -60C), 3.6V, 420mA continuous, 650 watt-hours/kg, **Wrap battery around winch and insulate - use** waste heat to improve battery efficiency.

Wet conditions. Need to prevent condensation/icing!

Lightning. Need faraday cage (conductive outer surface) plus static dischargers to protect the delicate electronics within.

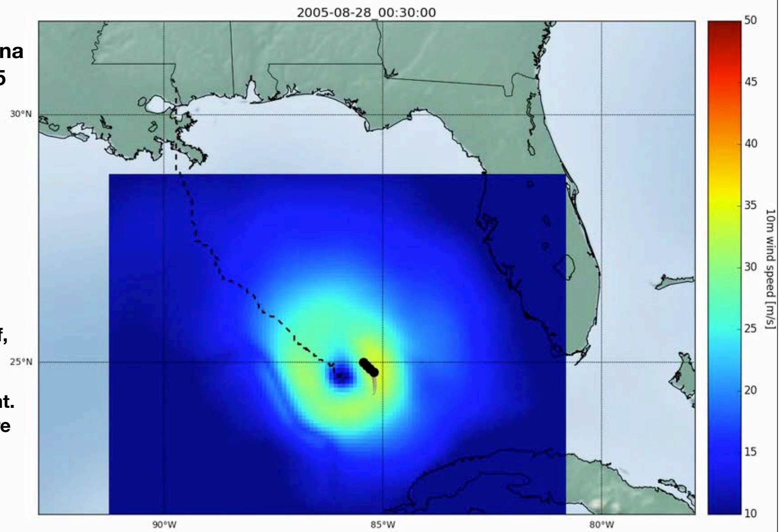
Low cost -> can afford many! Recover after landfall.

Estimated balloon specifications:
total mass: 2.5kg
volume (10km): $6m^3$



Hurricane Katrina
Aug 28-29, 2005

Simulated balloon trajectories



Note: Katrina increased from Cat 3 to Cat 5 in just 9 hours as it entered the gulf, passing over an unseasonably warm loop current. Difficult to capture such transitions without in situ continuous data!

UCSD

Thank you!

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