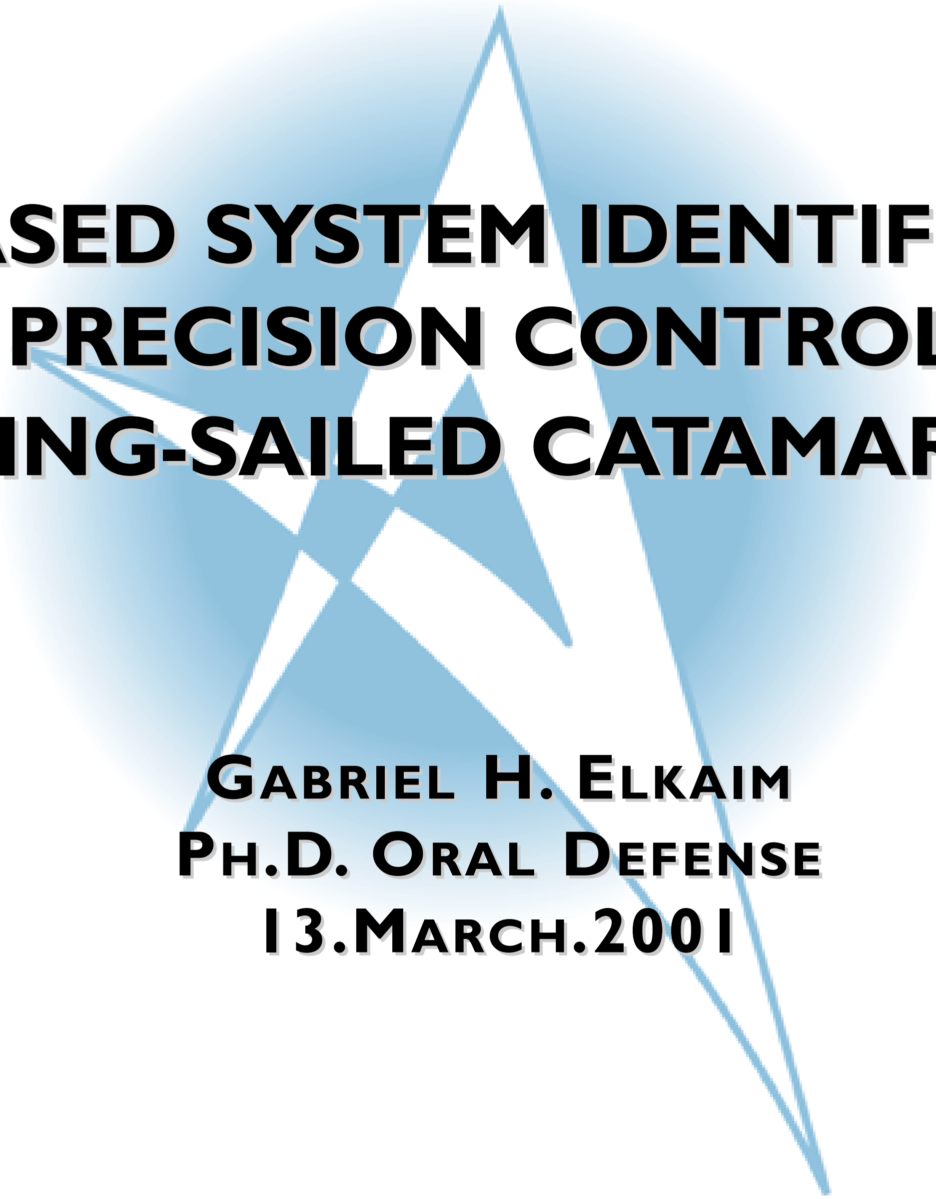
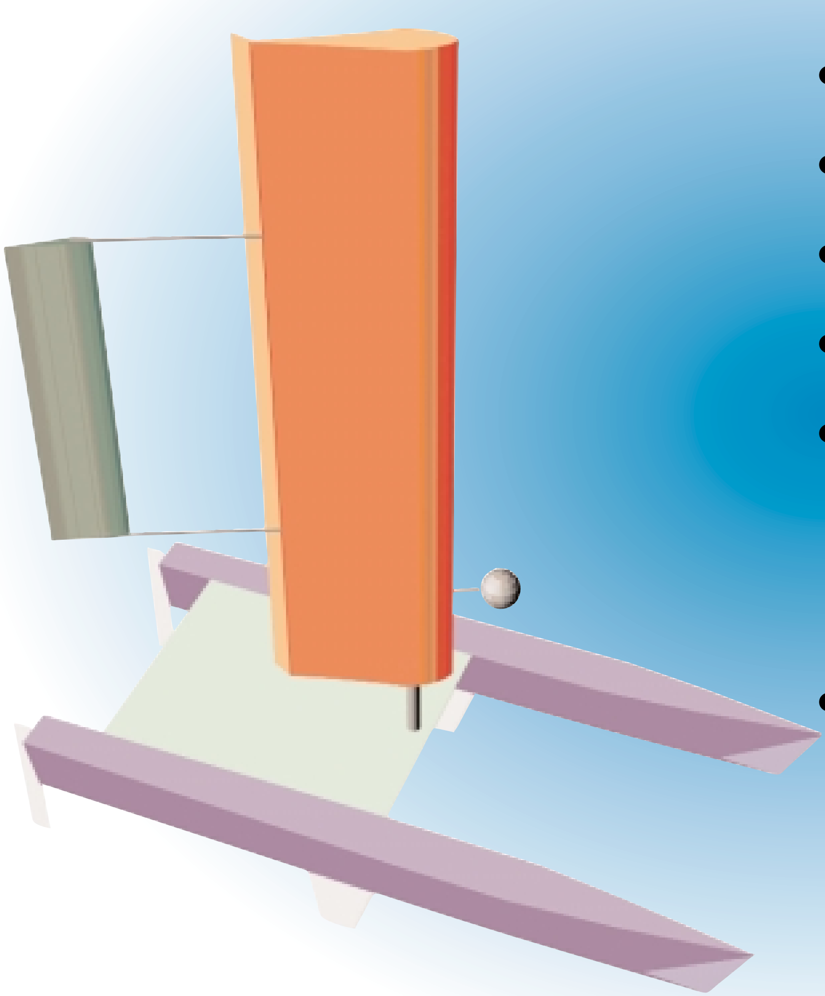


GPS-BASED SYSTEM IDENTIFICATION FOR PRECISION CONTROL OF A WING-SAILED CATAMARAN

Gabriel H. Elkaim
Ph.D. Oral Defense
13.March.2001

GOALS OF ATLANTIS PROJECT



- Wing-sail propelled
- GPS-based navigation
- Autonomous
- Self-sailing capability
- Self-guiding to better than 1 meter

- "Systems" thesis with efforts in structures, aerodynamics, and controls.

MOTIVATIONS

- Reduced fuel costs
- Increased speeds
- Replace “deep water” buoys with station keeping
- Remote weather and/or environmental monitoring
- Marine equivalent of UAV with infinite loiter time

CONTRIBUTIONS (1.3)

- Conceived, designed, built, and experimentally demonstrated an autonomous sailboat capable of precision control to better than 0.3 meters.

- Developed methodology to identify robust plant models and controllers that are invariant under velocity changes.

- Described optimization scheme for symmetric wingsail section based on requirements unique to sailing vehicles.

CONTRIBUTIONS (2.3)

- Developed and experimentally demonstrated novel quaternion-based attitude estimation algorithm from vector observations. [with Demoz Gebre]
- Developed and experimentally demonstrated novel method for calibrating any 3-axis sensor that requires no external reference. [with Demoz Gebre]

CONTRIBUTIONS (3.3)

- Identified robust model for Tractor and Implement System based on experimental data.

- Demonstrated method for robust identification of multiple implements and velocity configurations for GPS-guided tractor.

- Experimentally demonstrated precise control of GPS-guided tractor to 3 cm error with implement (vs. 12 cm for excellent human driver) based on identified models.

PRESENTATION MAP

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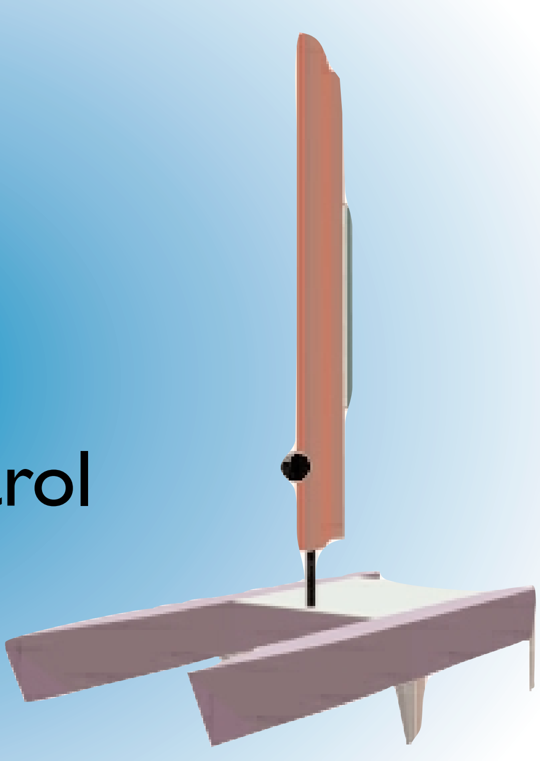
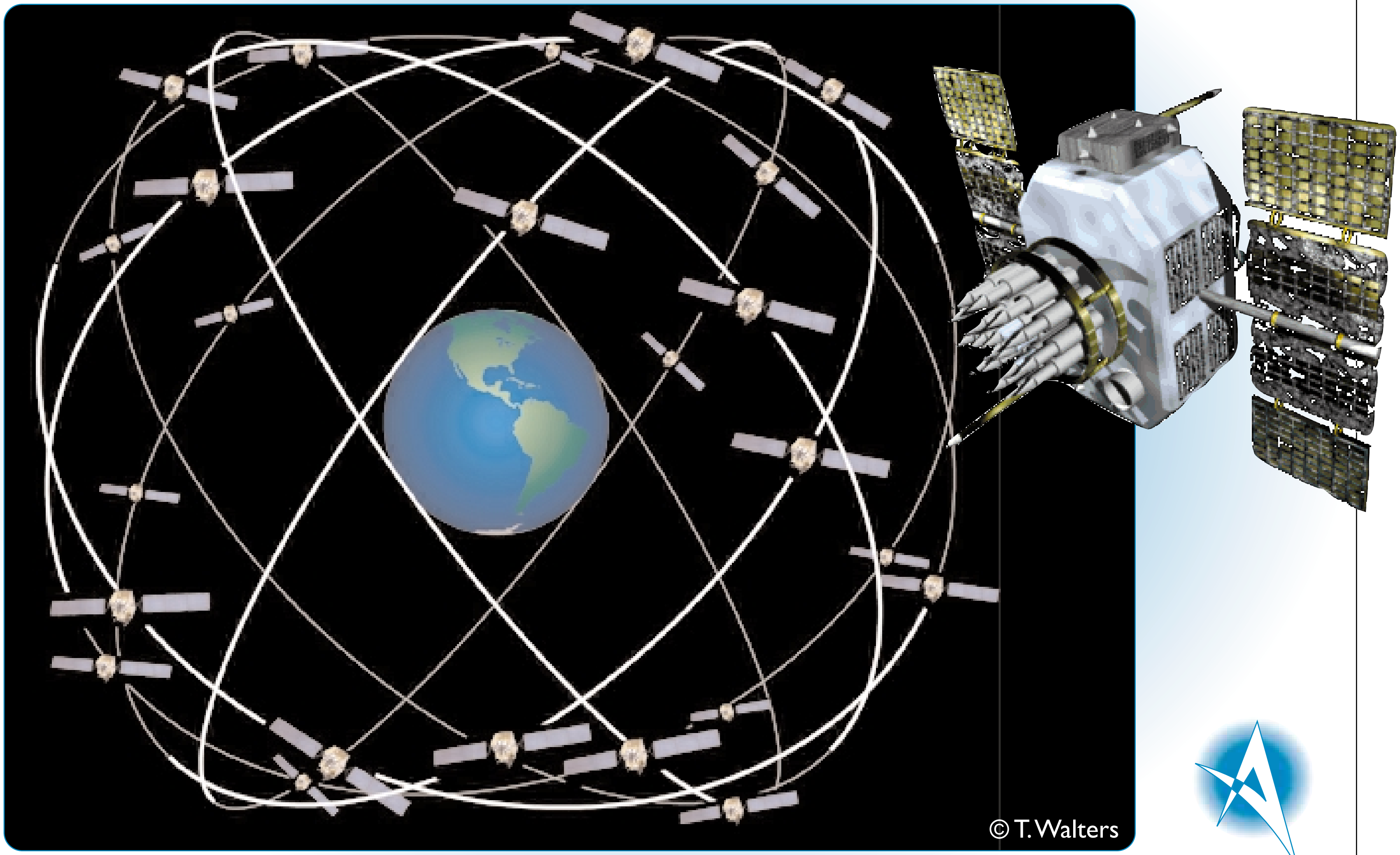
- Attitude System
- Propulsion System
- Identification and Control
- Experimental Results
- Conclusions
- Future Work



GLOBAL POSITIONING SYSTEM



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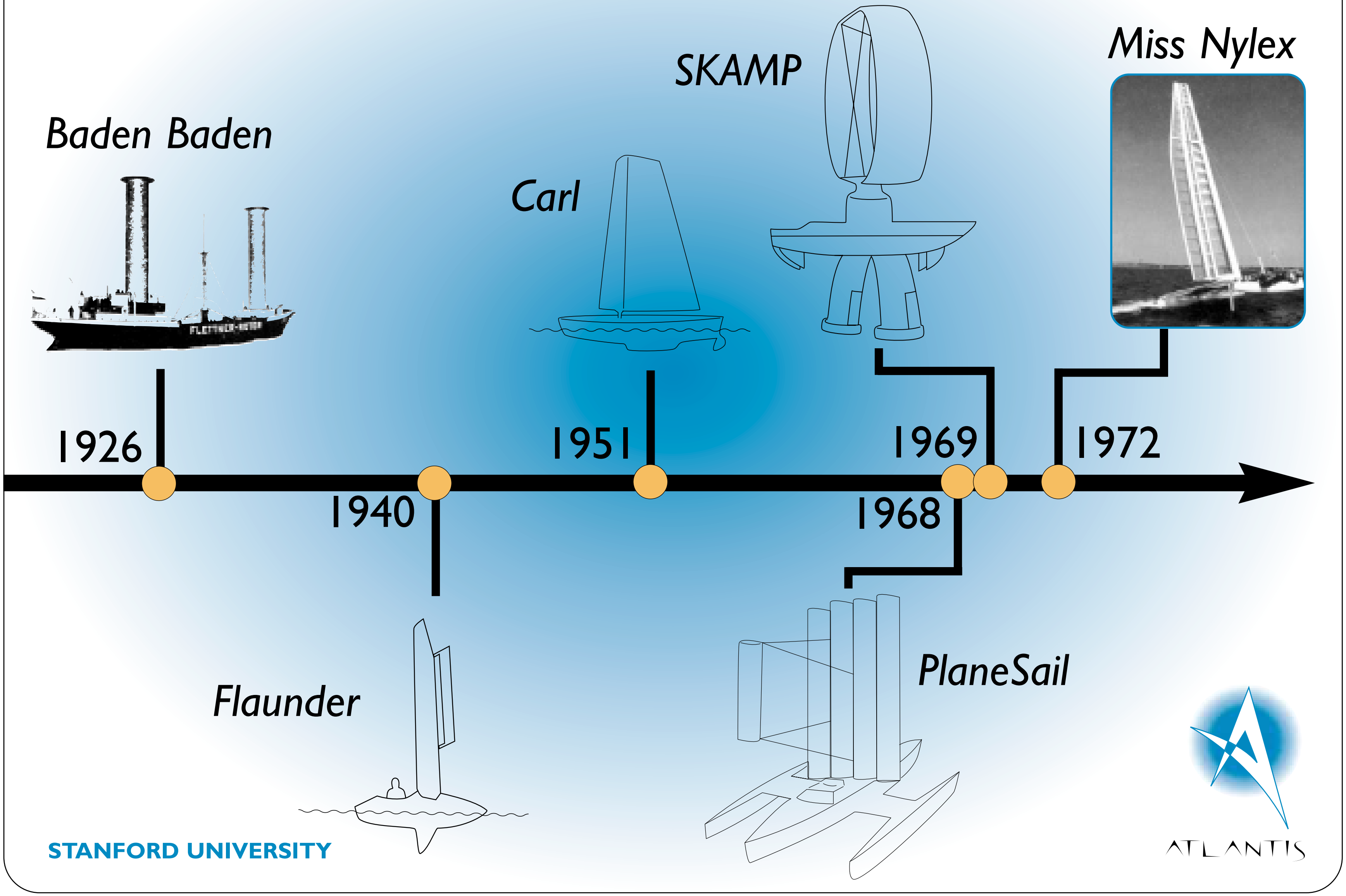
WINGSAIL HISTORY (1.3)



Baden Baden

1926

1940

Flaunder

Carl

1951

1968

PlaneSail

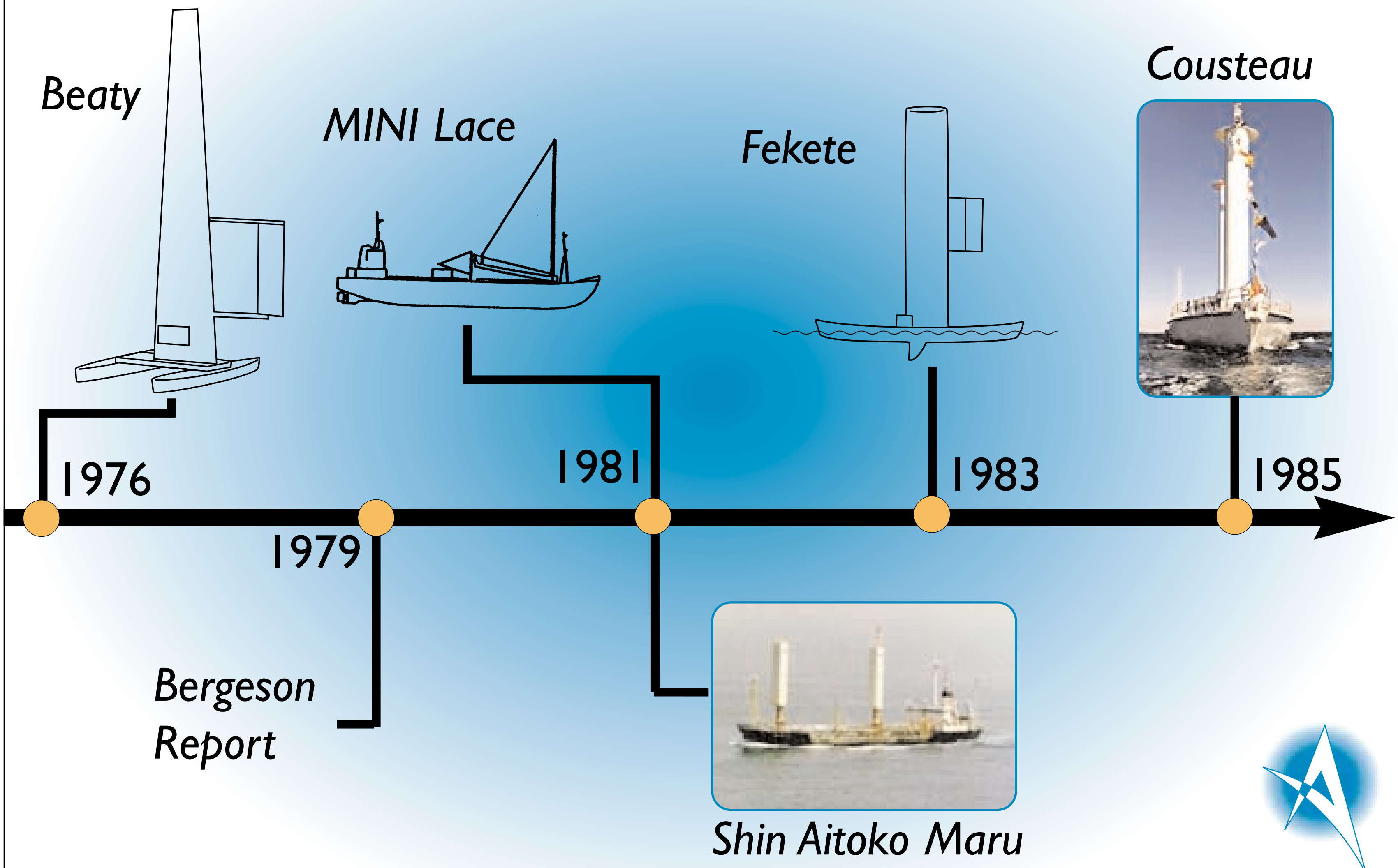
SKAMP

1969

Miss Nylex

1972

WINGSAIL HISTORY (2.3)



Beaty
1976

Bergeson Report
1979

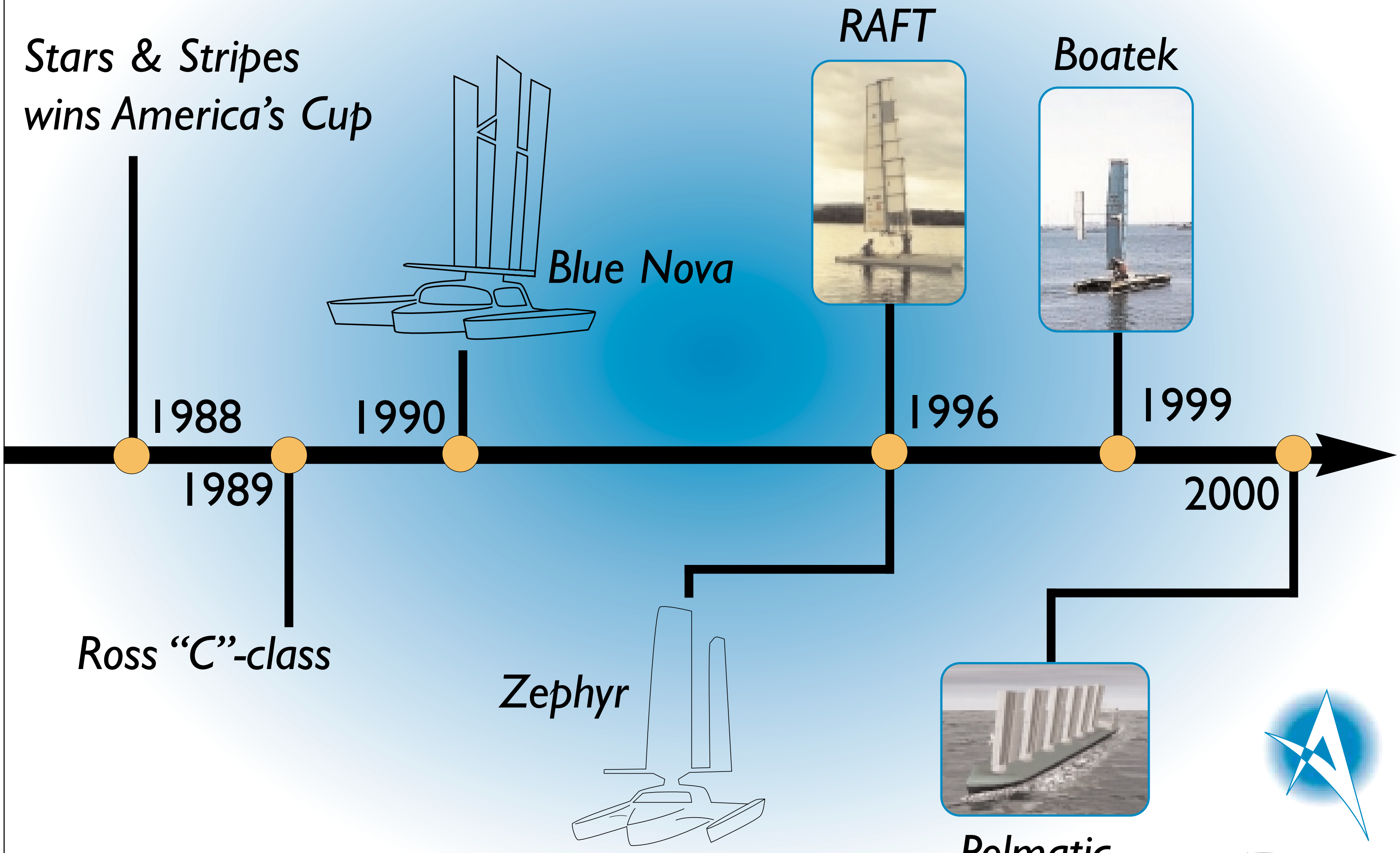
MINI Lace
1981

Shin Aitoko Maru
1981

Fekete
1983

Cousteau
1985

WINGSAIL HISTORY (3.3)



Stars & Stripes wins America's Cup

1988

Ross "C"-class

1989

1990

Blue Nova

Zephyr

RAFT

1996

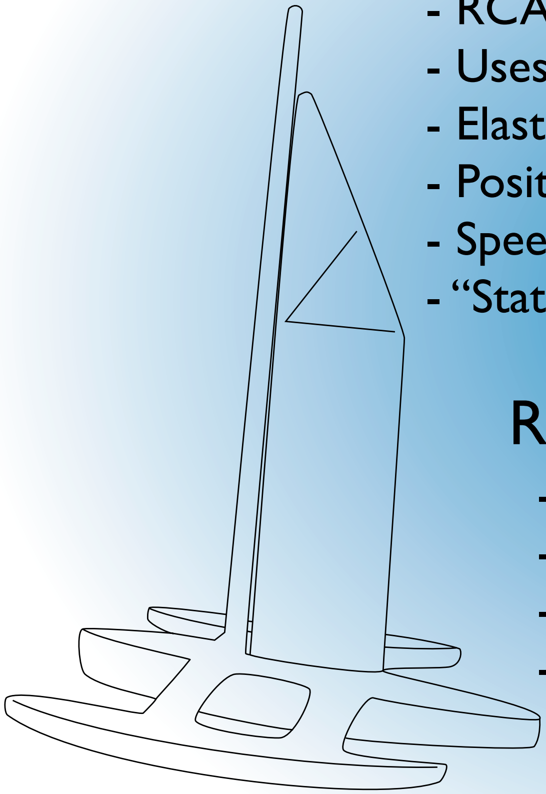
Boatek

1999

2000

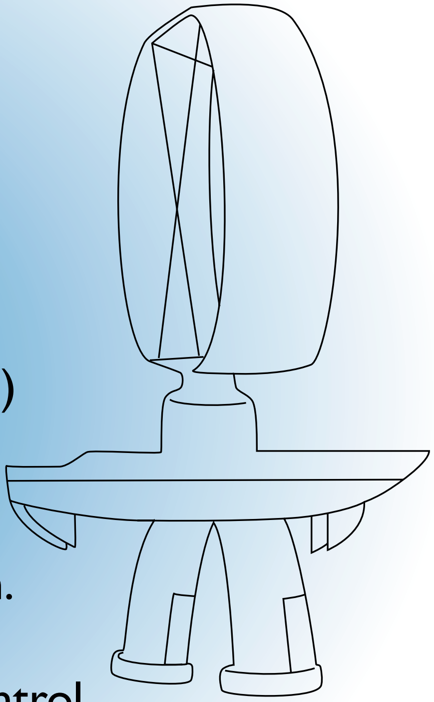
Pelmatic

AUTONOMOUS SAILBOATS



SKAMP project

- RCA Astro-Electronics division
- Uses two curved NACA 0030 wings
- Elastomeric hull
- Positioning via *Transit*
- Speed ~4 knots (2 m/s)
- "Station Keeping" within 0.2 nm (370 m.)



RELATIONSHIP project

- Technical University of Furtwangen.
- Conventionally sailed trimaran.
- Satellite link between boat and control.
- Currently anchored in Azores.

PRIOR ART

Attitude Estimation

- Wahba [1965] proposes two-vector problem.
- Bar-Itzhack [1985] extends solution to filter form.
- Creamer [1996] solves via two successive rotations.
- Hayward, et al [1999] constrains yaw, and solves for $\overset{n\to b}{[T]}$
- Murdin [2000] solves via eigenvalue decomposition.

Magnetometer Swinging

- Bowditch [1865] solves using known headings.
- Hine [1968] demonstrates complete error analysis.
- Psiaki [1990] uses orbital dynamics and gyros.
- Murdin [2000] solves via Information filter driven from an INS.

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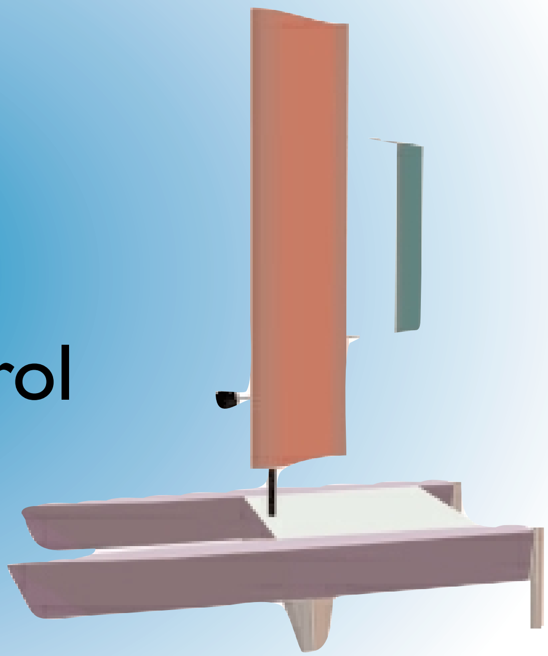


ATLANTIS' ANATOMY (1.2)

Wing:

free to rotate on bearings, propels the sailboat.

Ballast:

centers the wing's mass on the bearings.

Rudders:

provide steering, actuated via computer.

Tail:

keeps the wing adjusted to the wind.

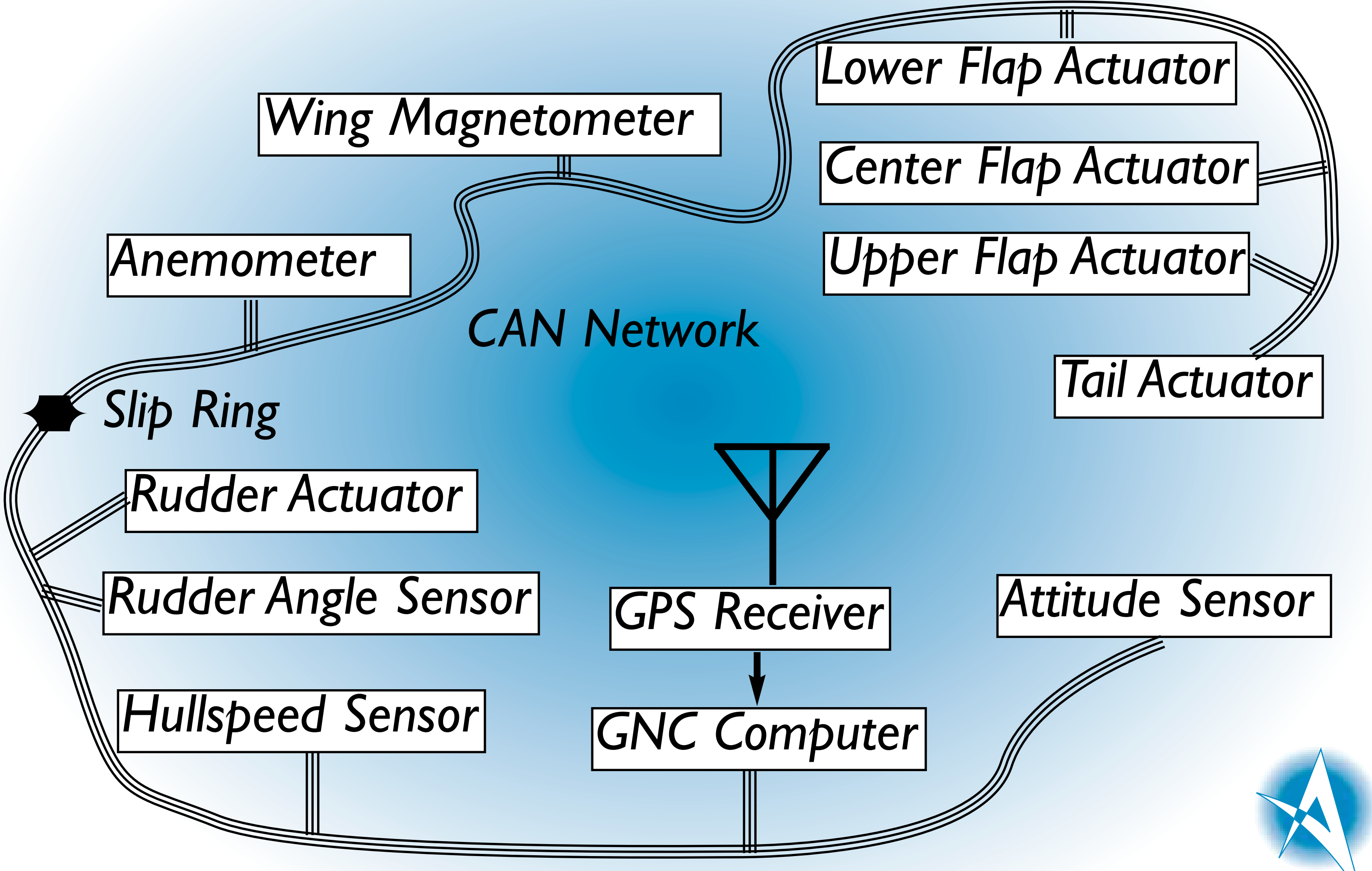
Anemometer:

senses the wind speed and direction.

Attitude:

senses the orientation of the sailboat.

ATLANTIS' ANATOMY (2.2)



Lower Flap Actuator

Wing Magnetometer

Center Flap Actuator

Anemometer

Upper Flap Actuator

CAN Network

Tail Actuator

Slip Ring

Rudder Actuator

Rudder Angle Sensor

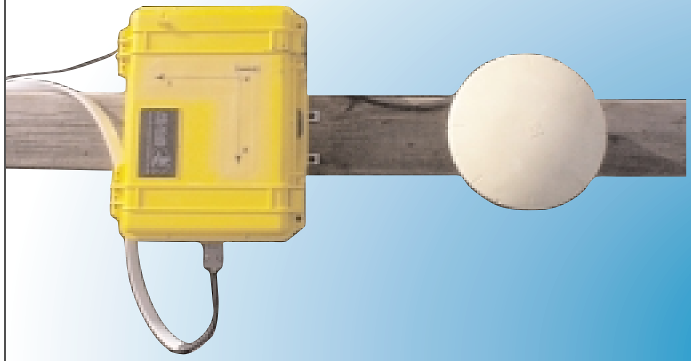
GPS Receiver

Attitude Sensor

Hullspeed Sensor

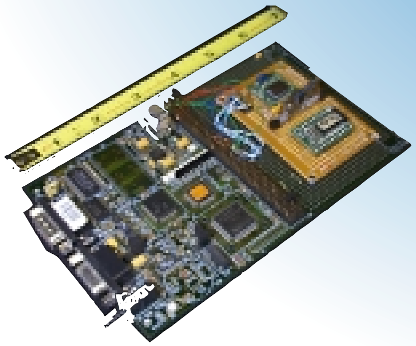
GNC Computer

ATTITUDE SYSTEM



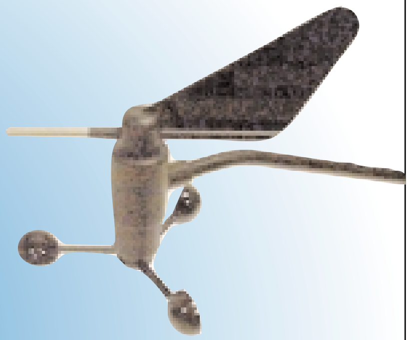
- Attitude system is required to create "synthetic" sensor at position different than GPS antenna.

- Uses a 3-axis magnetometer, and 2-axis accelerometer to determine attitude.

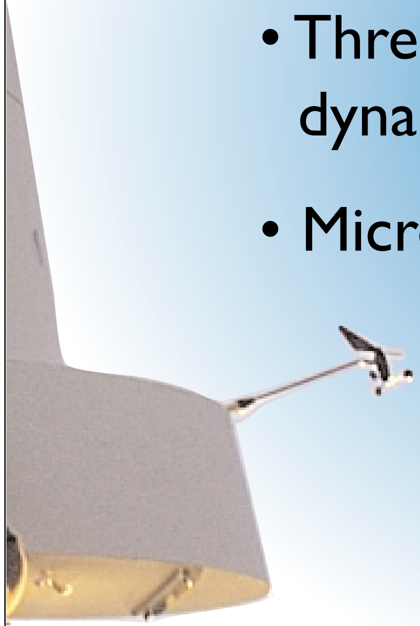


- Magnetometer heading is very sensitive to errors in pitch and roll.

ANEMOMETER



- Anemometer mounted on wingsail "pod," measures angle of attack of wingsail.
- Three cup anemometer measures dynamic pressure via differential drag.
- Microcontroller measures the time difference in clock cycles, wind velocity is inversely proportional to ΔT.



$$V_{wind} = K \frac{1}{\Delta T_{\mu Controller}}$$

WINGSAIL / PROPULSION

- 5.37 m. in height
- 1.25 m. chord
- 71 kg. mass
- mass balanced about quarter chord
- full-flying tail
- free to rotate about vertical axis on bearings
- construction materials are:
    - plywood ribs and skin
    - plywood shear webs
    - mylar covering
    - aluminum stub-mast

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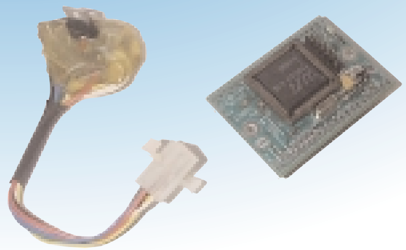
RUDDER ACTUATOR

- Mechanical lead-screw translates rotary motion to rudder angle
- Fractional horsepower brushed-DC motor
- PWM from Zanthic/Seimens SAB-505CA µController
- 500 count-per-revolution encoder
- Infineon 5-A H-bridge motordrive chip



RUDDER ANGLE SENSOR

- The rudder angle sensor is a lohet mounted in between two magnets.
- The output is proportional to the flux crossing the lohet plane:

$$V_{output} = K\sin(\Theta)$$

- The rudder was calibrated by deflecting to +/-30 and +/- 45 and zero degrees as measured perpendicular to the hull end.

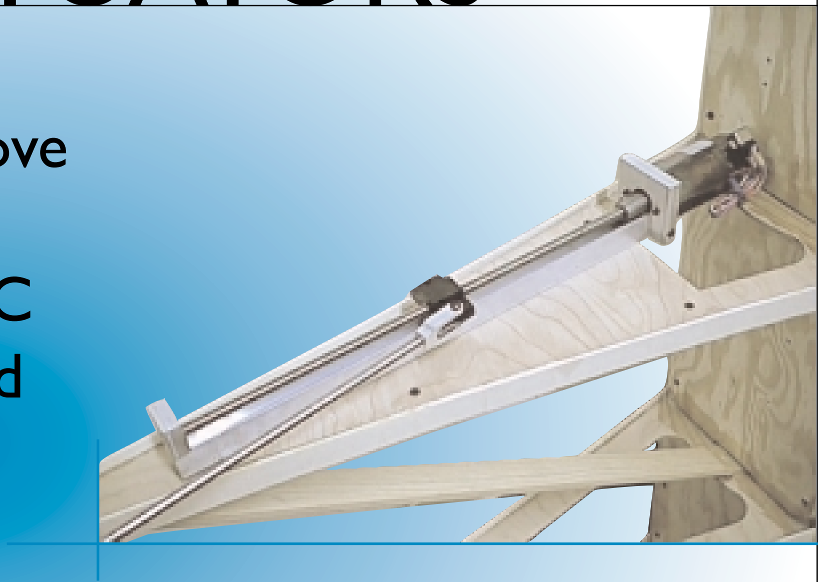
HULLSPEED SENSOR

- Magnetic "Paddle-Wheel" and hall-effect sensor buried on hull centerline.
- Motion based on paddle wheel being semi-submerged in moving water.
- Four pulses per revolution.
- Systematically very similar to anemometer.
- Calibration based on matching GPS velocity and Hullspeed for out and back course using electric trolling motor.

GNC BOX

- Waterproof case for electronics.
- Pentium class GNC computer.
- DC/DC converter runs main computer off of system 12V bus.
- Trimble Ag122 GPS receiver communicates to GNC on RS-232.
- ESD CAN dongle provides CAN interface to GNC computer.

FLAP/TAIL ACTUATORS



- Actuators are used to move trailing edge flap and tail
- Actuators are brushed DC motors, connected to lead screws
- Push rods link the lead screws and the control horns
- Motors are controlled via a μcontroller using PWM drive

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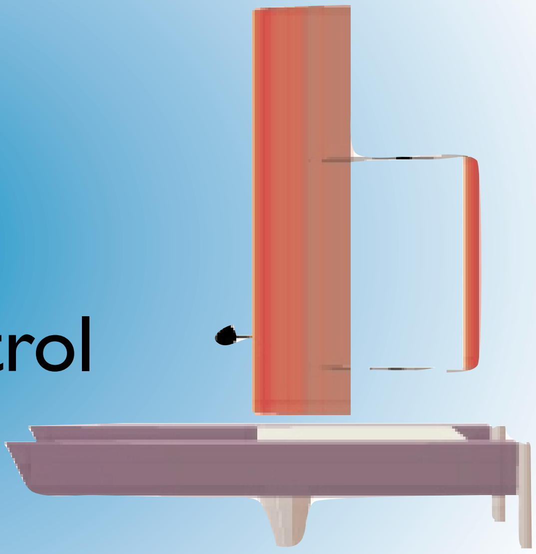
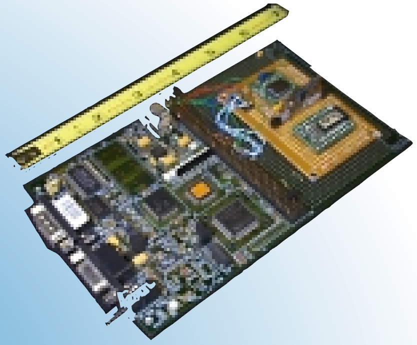
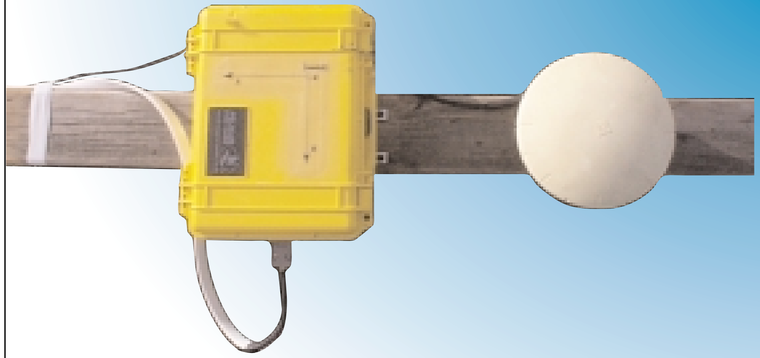


ATTITUDE SYSTEM

- Attitude is computed based on vector "matching."

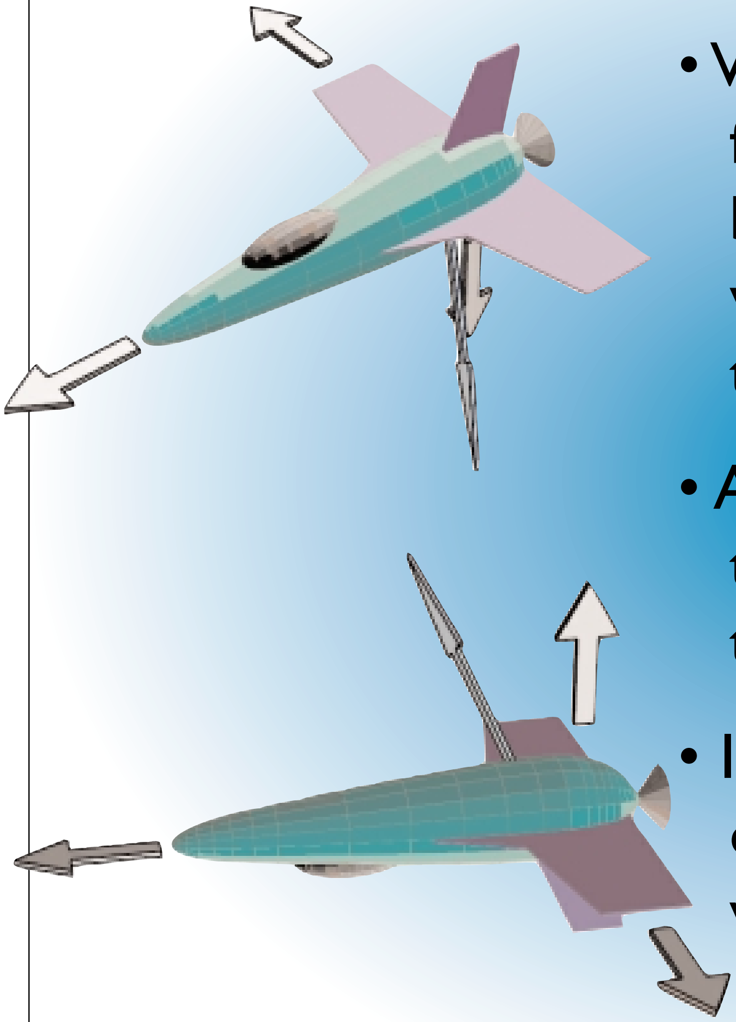


- A new quaternion attitude estimation algorithm was developed to take advantage of low-cost sensors.



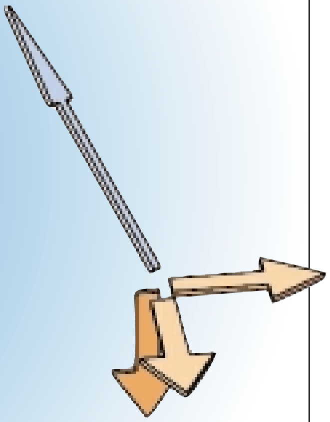
- Uses a 3-axis magnetometer, and 2-axis accelerometer to determine attitude.

VECTOR MATCHING



- Vector matching consists of finding the rotation that brings the measured (body) vector into alignment with the known (inertial) values.
- Ambiguity of rotation about the vector requires at least two vectors to solve.
- Implemented with quaternion-based algorithm where:

$$q_{true} = q_e \otimes \hat{q}$$



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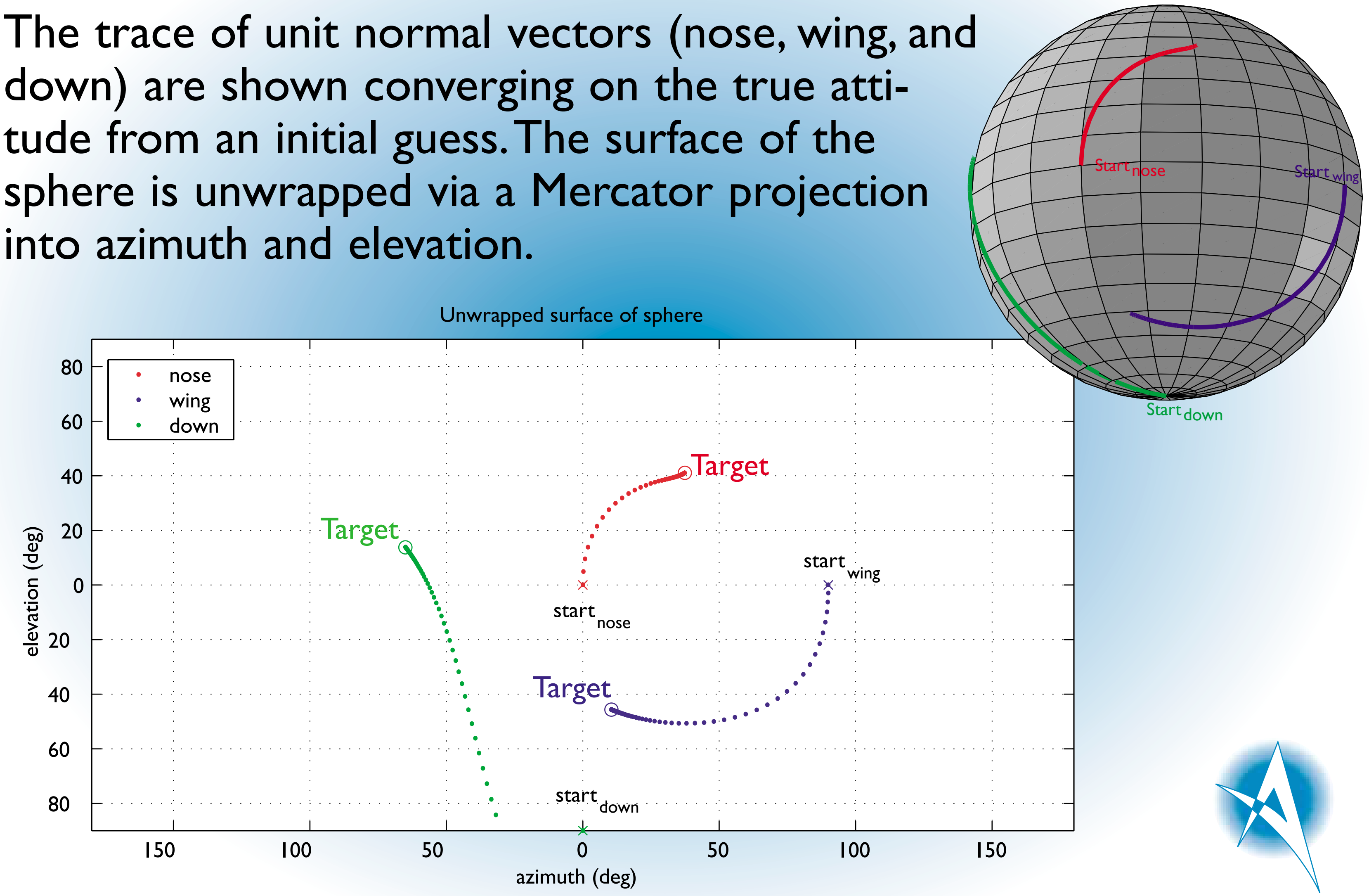
PERFORMANCE ON SIMULATED DATA

The trace of unit normal vectors (nose, wing, and down) are shown converging on the true attitude from an initial guess. The surface of the sphere is unwrapped via a Mercator projection into azimuth and elevation.



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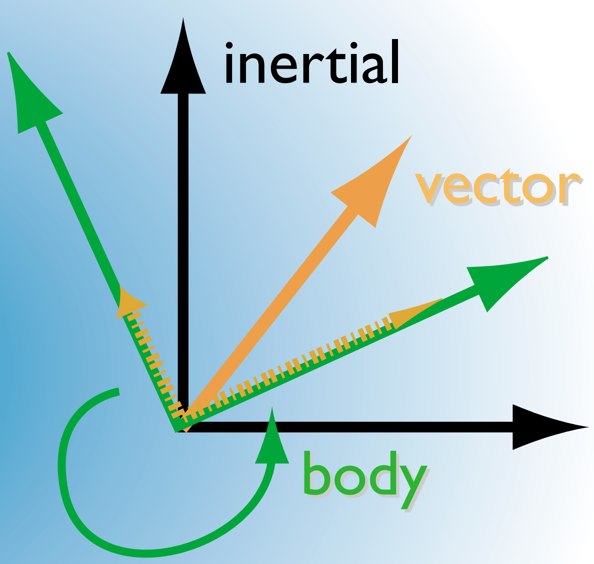
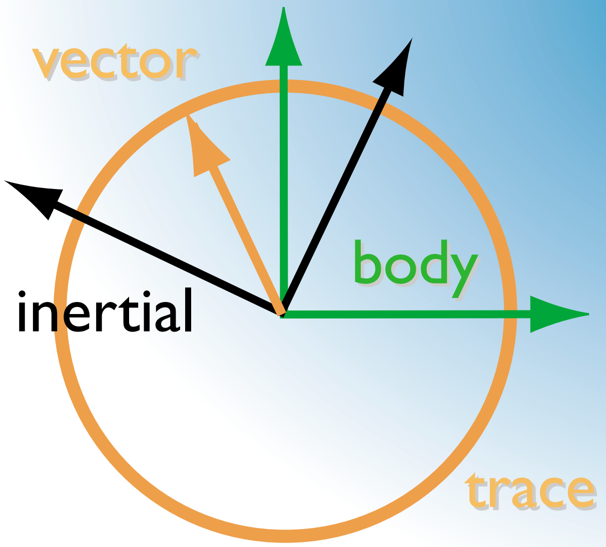
MAGNETOMETER CALIBRATION

- Honeywell HMC2300 3-axis magnetometer, measures earth's magnetic field in body frame.
- Hard Iron (bias) and Soft Iron (scale factor) errors need to be removed by calibration.
- Two-step calibration method requires no additional information or instrumentation.
- Biases and Scale Factors solved in Measurement domain.

IDEAL 2-D SENSOR TRACE

- A vector is constant in the inertial frame, but is measured in the body frame.





- As the body frame is rotated the components measured along each axis trace out a circle.

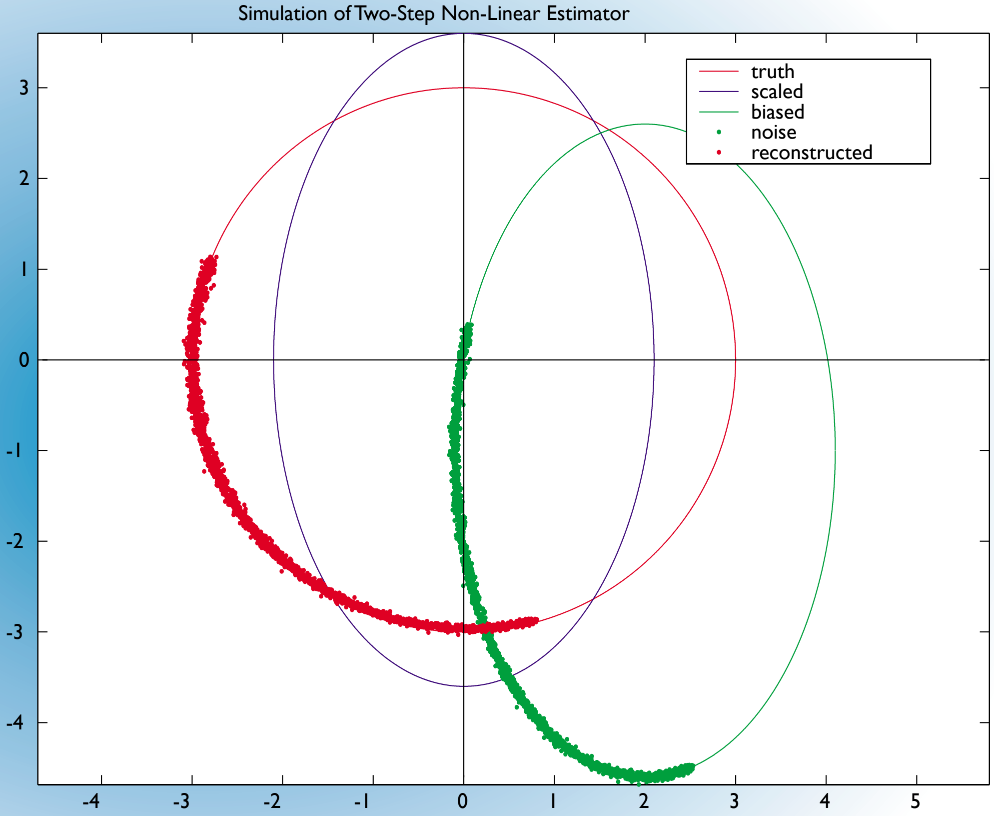
2-D MAGNETOMETER SIMULATION

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} = R^2$$

$$\left[x_i^2\right] = \left[2x_i \quad -y_i^2 \quad 2y_i \quad 1\right]\begin{bmatrix} x_0 \\ k_2 \\ k_2 y_0 \\ k_1 - x_0^2 - k_2 y_0^2 \end{bmatrix}$$

$$k_1 = a^2 R^2$$

$$k_2 = \frac{a^2}{b^2}$$



- Break the estimation into two parts: Least squares estimation of non-intuitive states, then algebraic manipulation of states to extract relevant parameters.
- Can be solved with only a small part of the circle.

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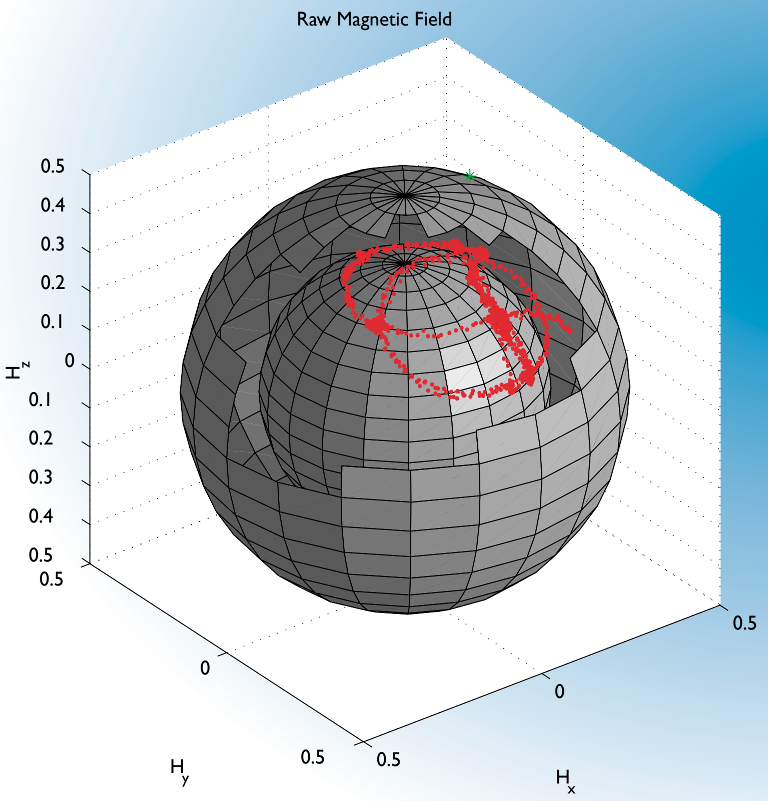
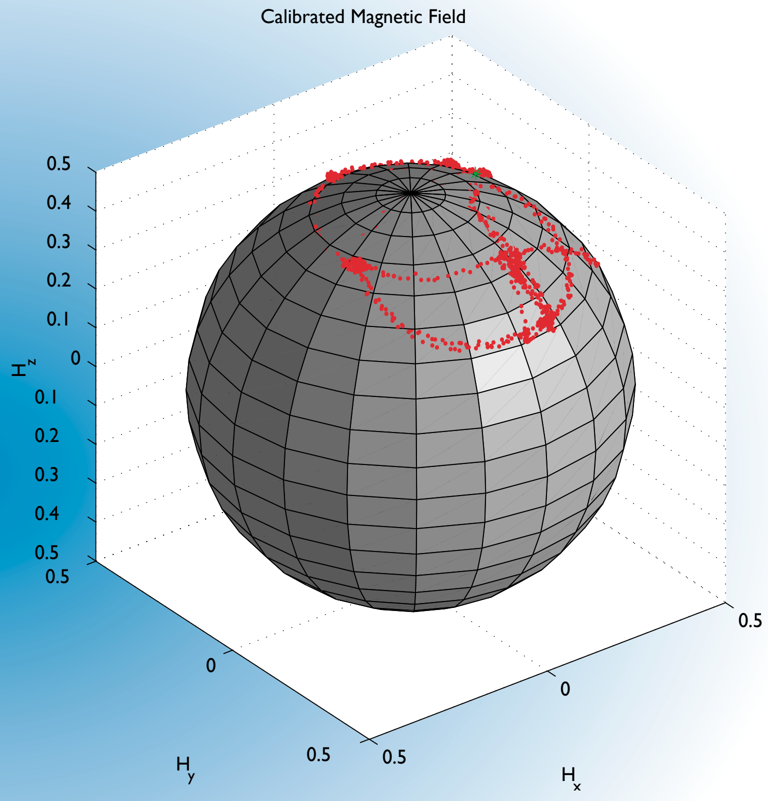
EXPERIMENTAL SETUP (GROUND)

- Attitude box secured to end of a long wooden boom, with magnetometer recording data at 100 Hz.
- Honeywell navigation grade INS records attitude for later comparison.
- Setup is pitched, rolled, and yawed to generate data for calibration run.
- Experiment repeated several times for validation run.

EXPERIMENTAL RESULTS (1.2)

- Before calibration, trace is poor match to the surface of the sphere.





- After calibration, trace is an excellent match to surface of sphere.

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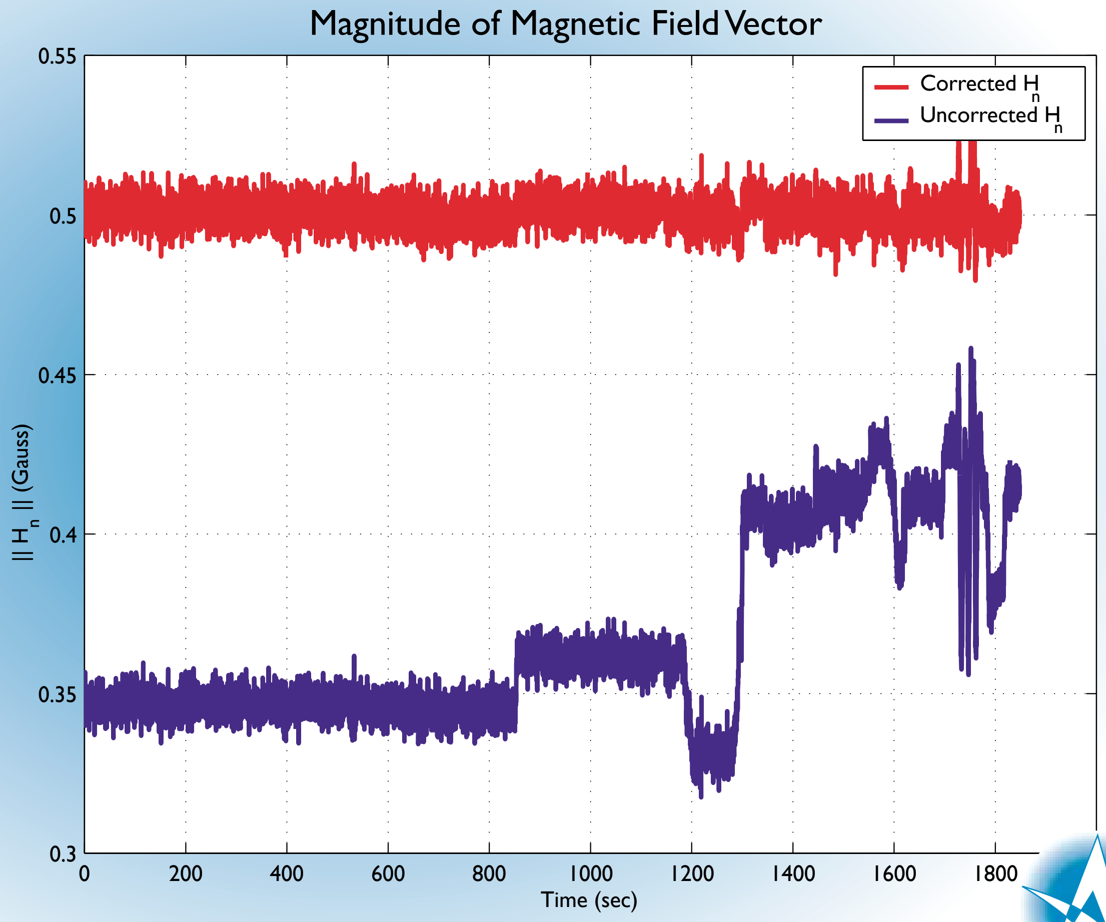
EXPERIMENTAL RESULTS (2.2)

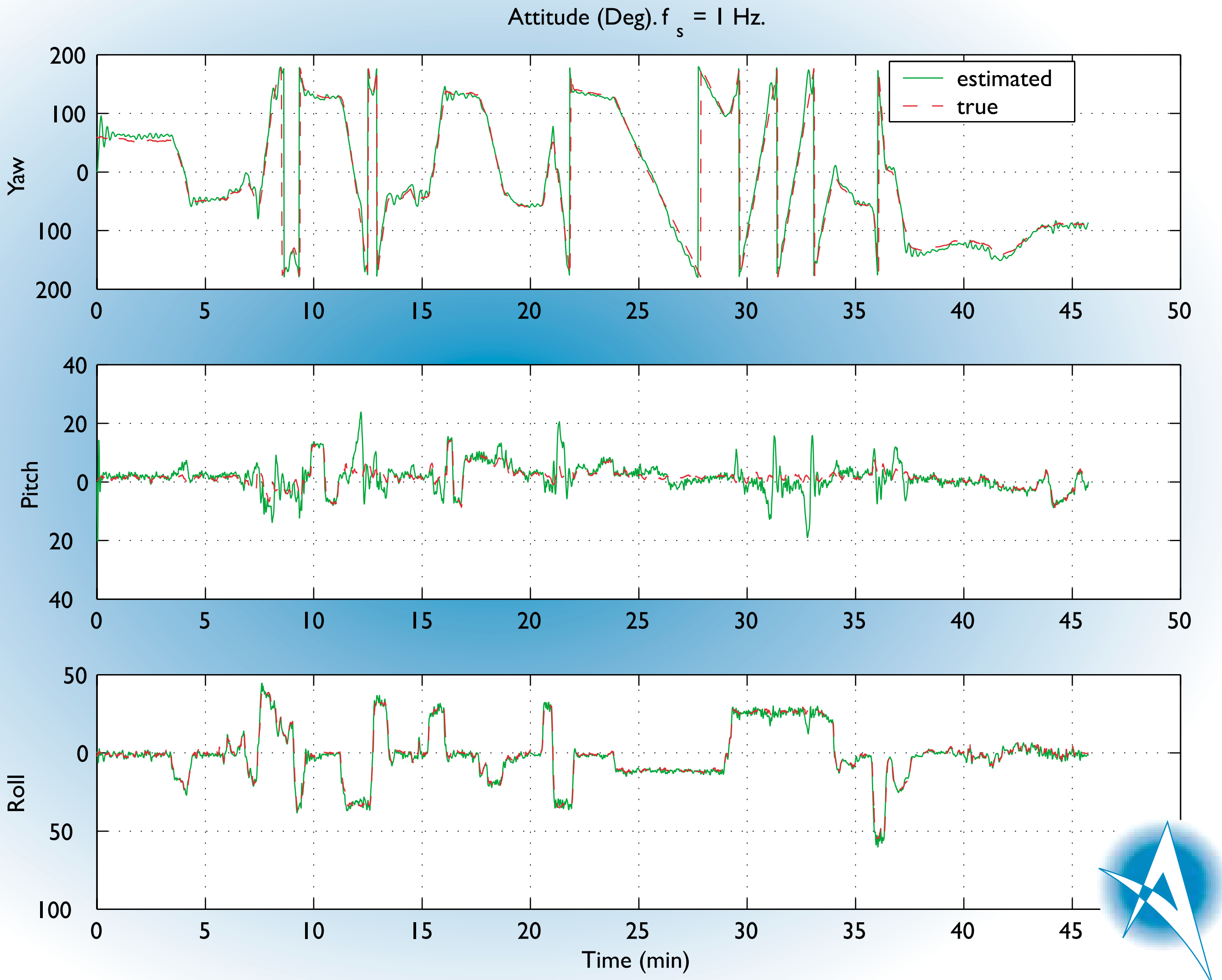
- After calibration, validation run shows a very constant magnitude of magnetic field vector.

- Before calibration, the magnitude of the magnetic field varies greatly with pitch and roll inputs.



QUATERNION ATTITUDE ON REAL DATA

- Real data based on flight test of QueenAir from Livermore to San Jose.
- Truth is from short baseline GPS attitude.
- Coordinated turns through due East and due West (Yaw is +/- 90) violated conditions of having two non-collinear vectors.



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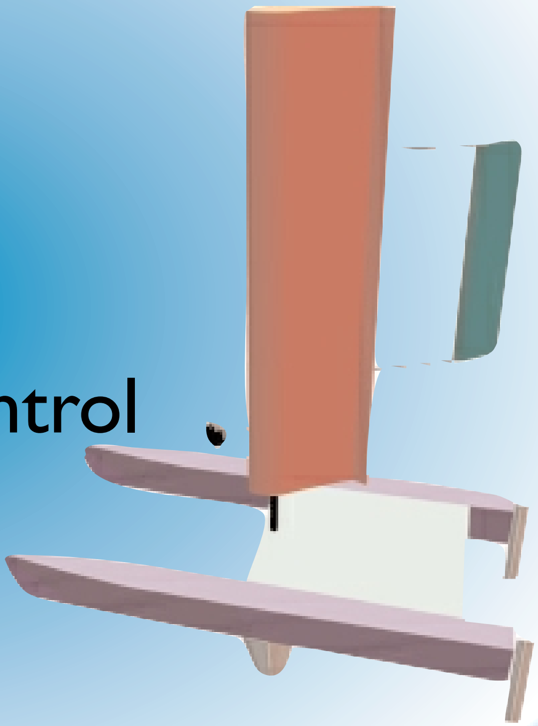
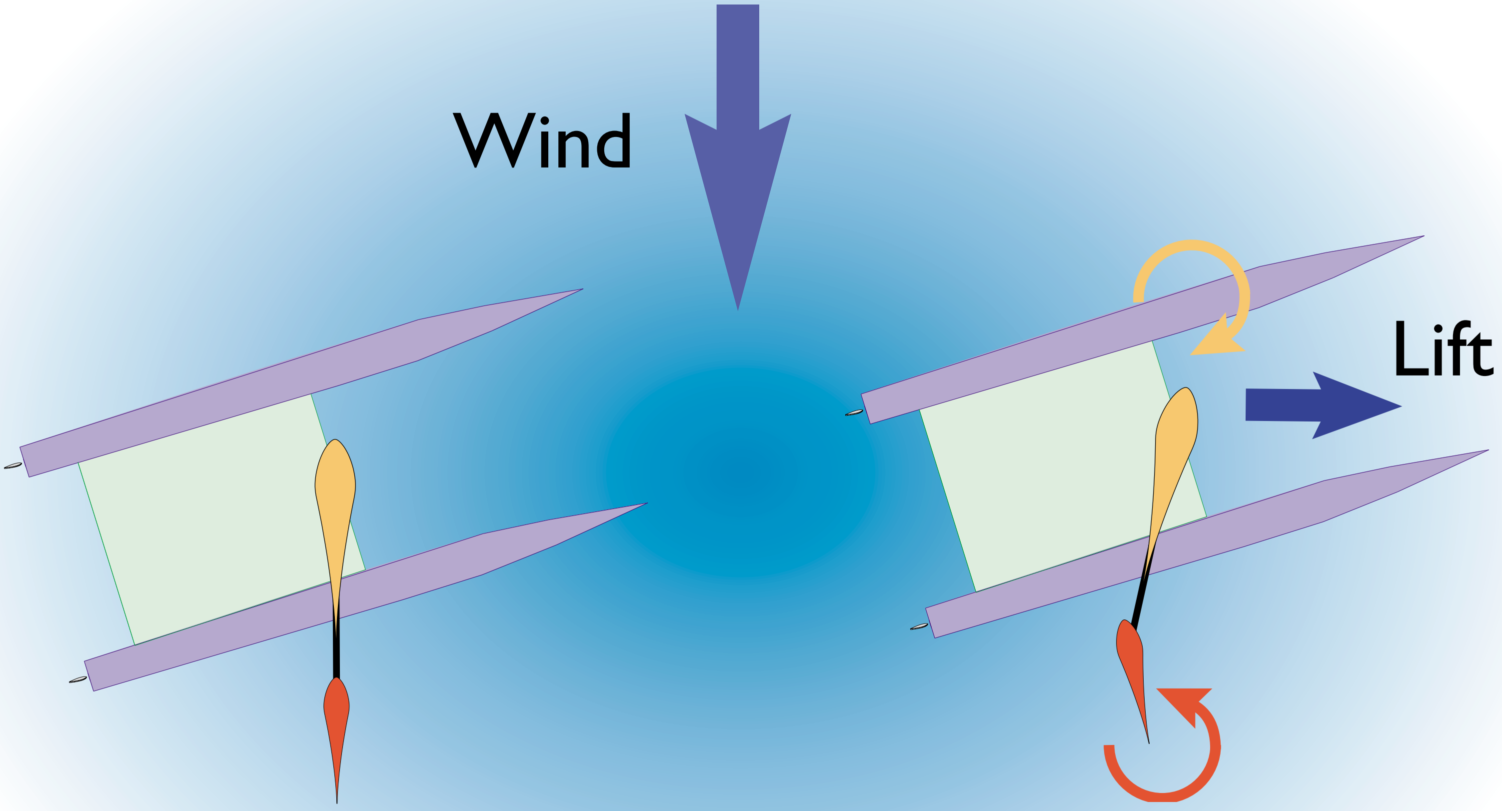


WHY USE A WINGSAIL?

- Self-trimming WingSail can be controlled with very small actuators.
- WingSail can be self-trimming within a large range of wind directions.
- WingSail is more efficient:
  - Aeroelastically stable
  - Higher lift/drag ratio
  - Greater $C_{L_{max}}$
- Tacking and Jibing become very docile maneuvers.

HOW DOES THE WINGSAIL WORK?



- Tail deflection causes WingSail to rotate on bearings, generating an “angle of attack” to the wind, and thus lift.
- Lift on WingSail pulls boat forward through water.

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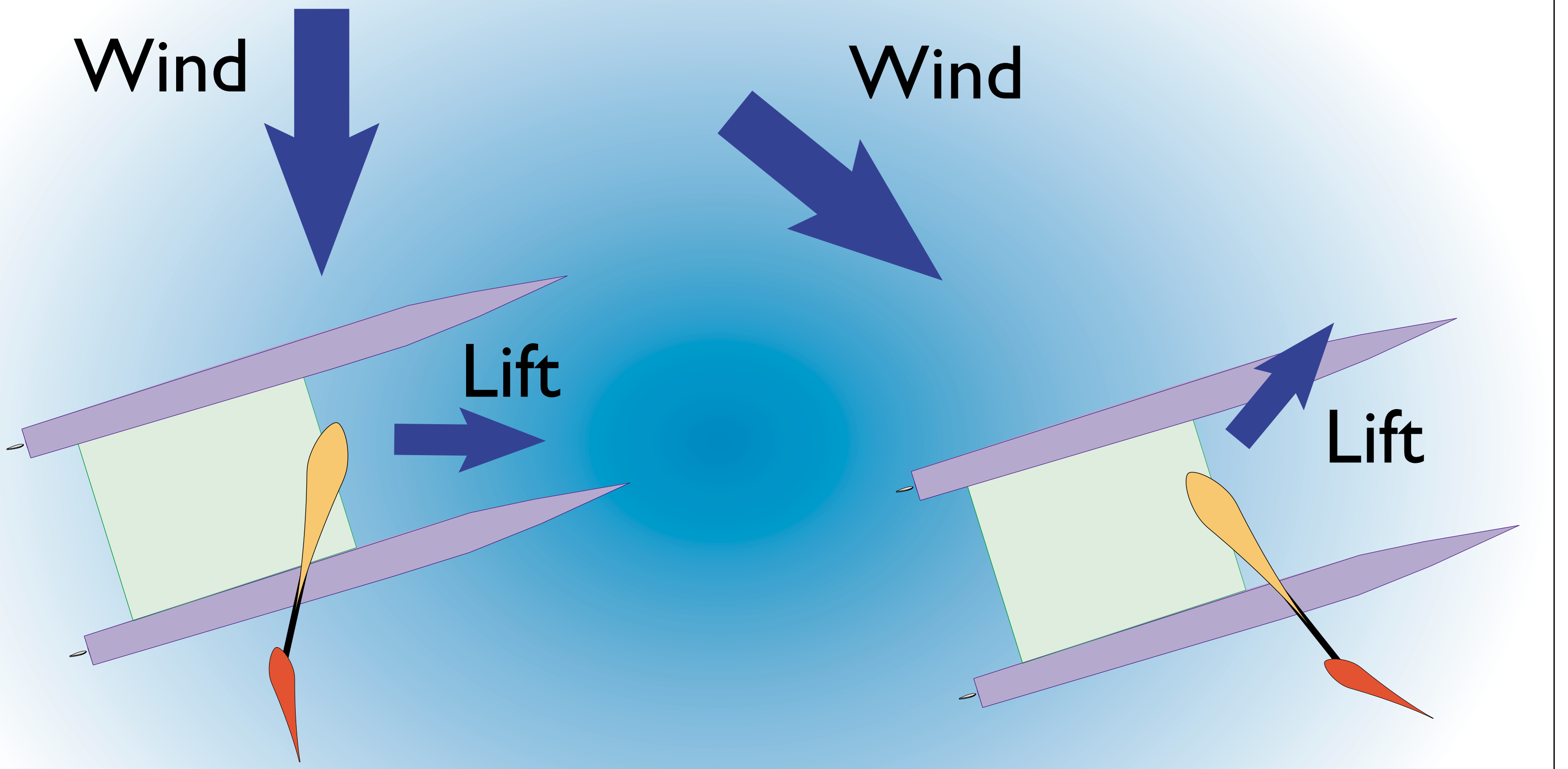
HOW DOES SELF-TRIMMING WORK?



- A change in the wind direction causes a load on the tail which rotates the WingSail on its bearings.
- The WingSail orientation remains constant relative to the wind!

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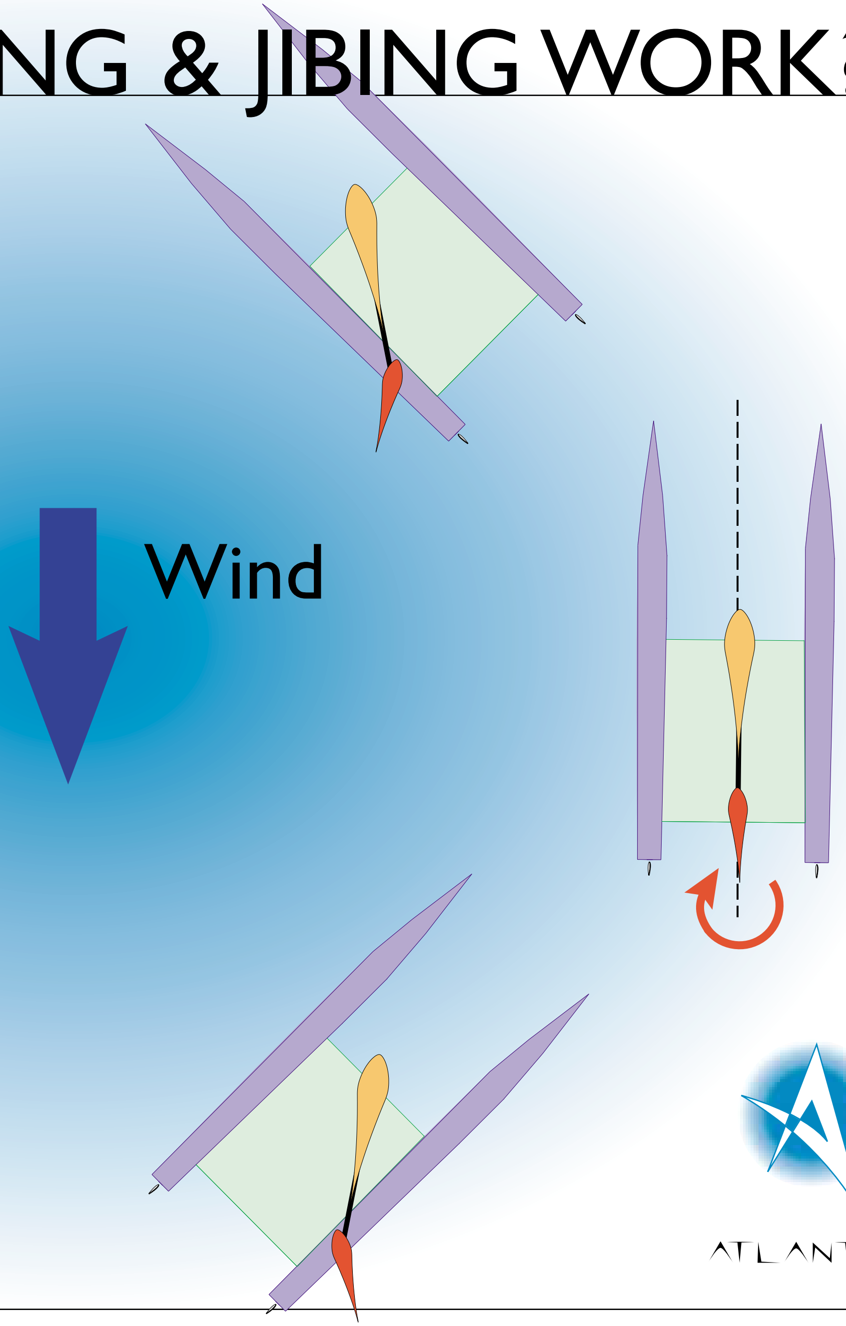
HOW DO TACKING & JIBING WORK?

- The WingSail is tacked or jibed by centering the tail as the wind passes the center-line of the boat.

- The tail is then turned to the opposite side of the WingSail and the tack or jibe is complete.

- The only difference between a tack and a jibe is the orientation of the WingSail with respect to the boat.

- The WingSail remains at a constant orientation to the wind.



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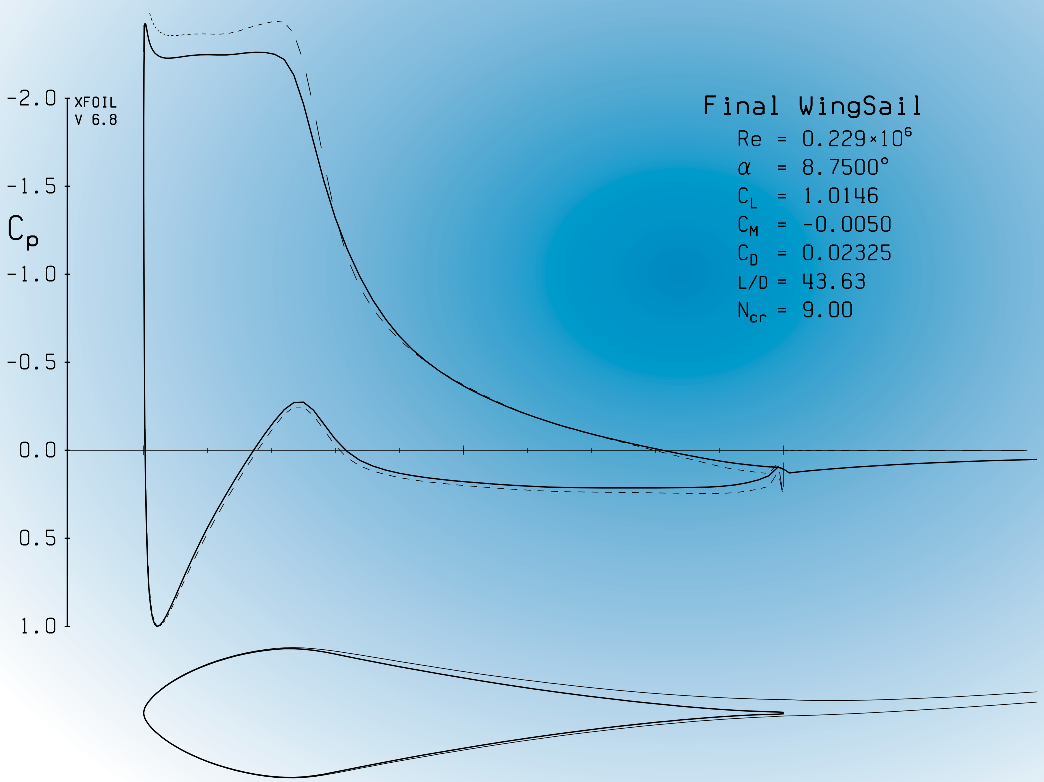
AIRFOIL DESIGN METHODOLOGY

- Low Reynolds number (<300,000) requires special design considerations.
- Conventional symmetric airfoil perform very poorly.
- Large, blunt leading edge for good $C_{L_{max}}$
- Trip boundary layer at maximum thickness.
- Flat "rooftop" pressure distribution until trip point.
- Long, slow pressure recovery required.

FINAL AIRFOIL SECTION

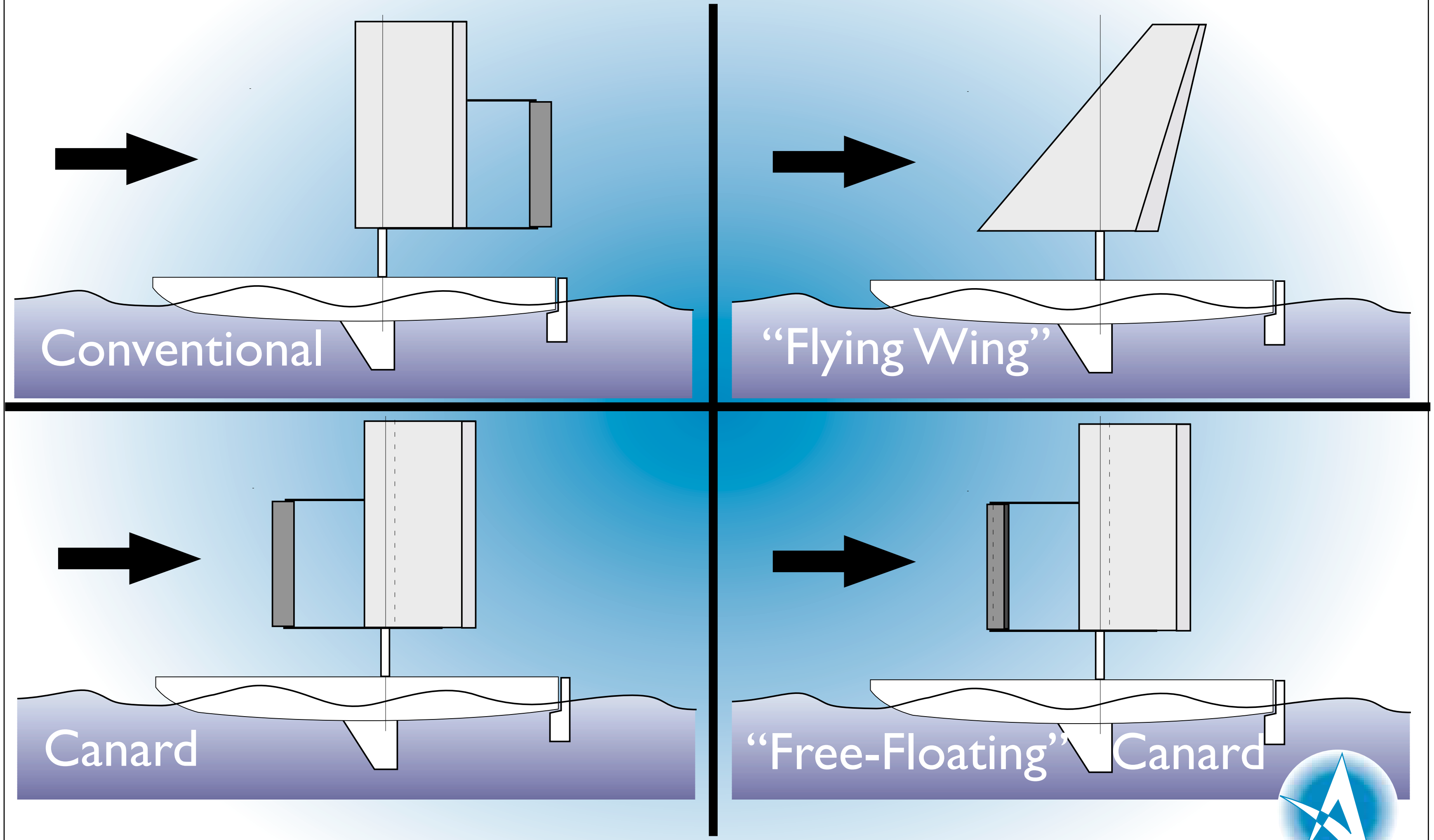
WingSail:



CONFIGURATION CONSIDERATIONS

- The WingSail needs to weather vane into the relative wing, and at the same time, trim a large maximum lift coefficient ($C_{L_{max}}$).
- Control power, or pointing ability
- Mass balance about pivot point
- Minimum swept-radius WingSail
- Mechanical complexity
- Stability requires: $\partial C_m/\partial \alpha < 0$
- Trim requires: $C_m = 0$

WINGSAIL CONFIGURATIONS



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BASIC STRUCTURAL LOADING

Physical Parameters:

$b = 5.37$ m.

$c = 1.425$ m.

$S = 7.65\ m^2$.

$m = 324$ kg.

$AR = {}^{b}/_{c} = 3.765$

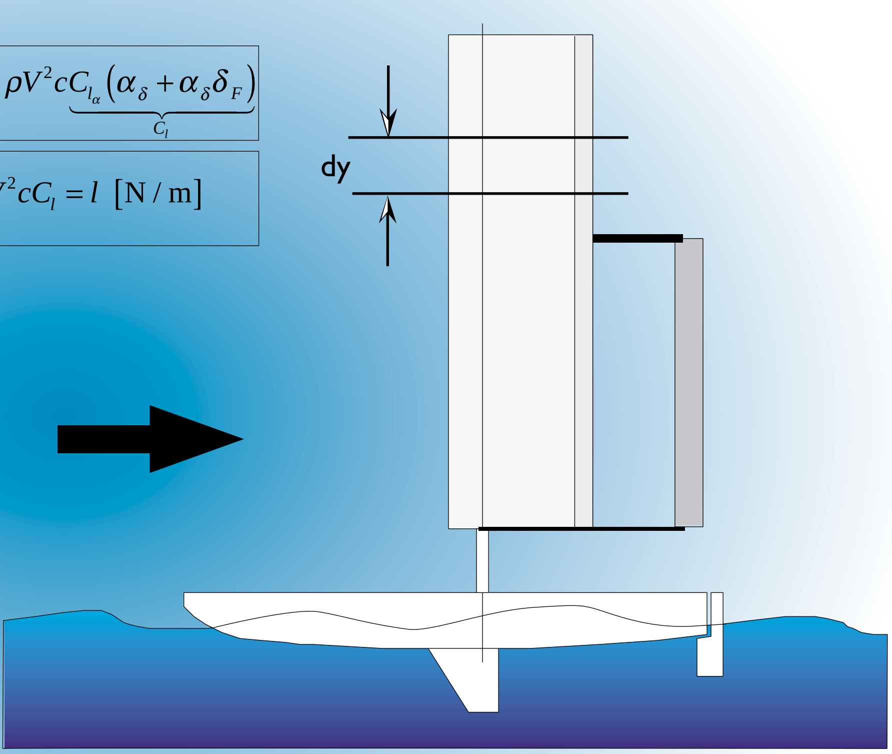
$C_{L_{max}} = 1.8$

$\rho_{air} = 1.225\ kg/m^3$

$g = 9.81\ m/s^2$.

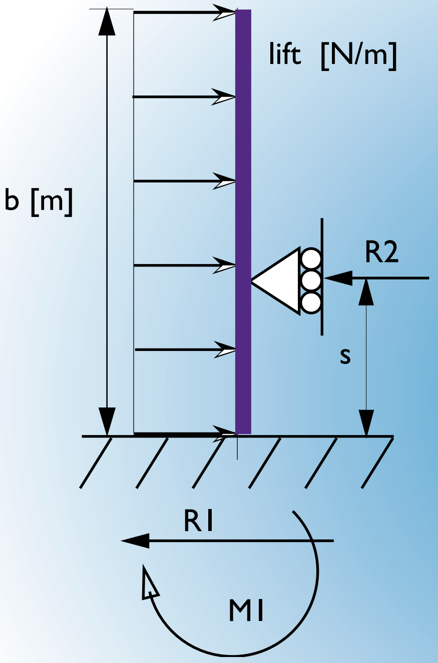
$$l = \frac{1}{2}\rho V^2 c \underbrace{C_{l_\alpha}\left(\alpha_\delta + \alpha_\delta \delta_F\right)}_{C_l}$$

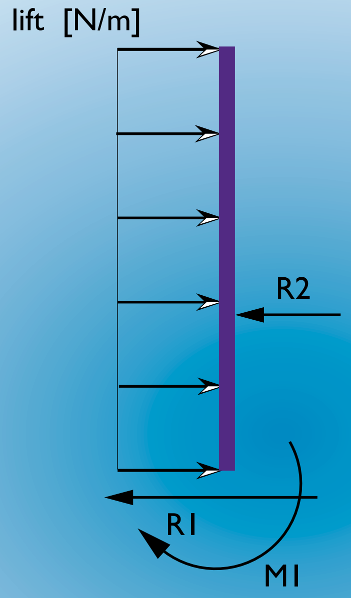
$$\frac{1}{2}\rho V^2 c C_l = l \ \ [\mathrm{N/m}]$$



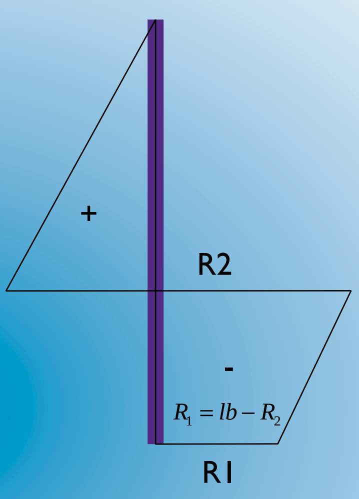
$$L = \int_h^{h+b} l\,dy = \int_h^{h+b} \frac{1}{2}\rho V^2 c C_l\,dy = \frac{1}{2}\rho V^2 c C_l \int_h^{h+b} dy = \frac{1}{2}\rho V^2 c C_l [b] = lb = L \ \ [\mathrm{N}]$$

WING SPAR STRUCTURAL LOADS





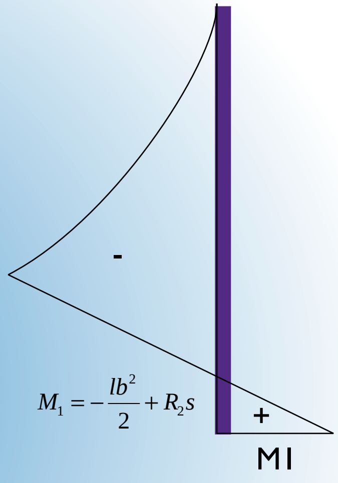
Forces



$R_1 = lb - R_2$

$V = lx - R_2\langle x-\gamma\rangle^0$

Shear



$M_1 = -\frac{lb^2}{2} + R_2 s$

$M = -\frac{lx^2}{2} + R_2\langle x-\gamma\rangle$

Moments

$$EIw'' = -M = \frac{lx^2}{2} - R_2\langle x-\gamma\rangle$$

$$EIw' = \frac{lx^3}{6} - R_2\frac{\langle x-\gamma\rangle^2}{2} + c_1$$

$$EIw = \frac{lx^4}{24} - R_2\frac{\langle x-\gamma\rangle^3}{6} + c_1 x + c_2$$

Evaluate B.C's:

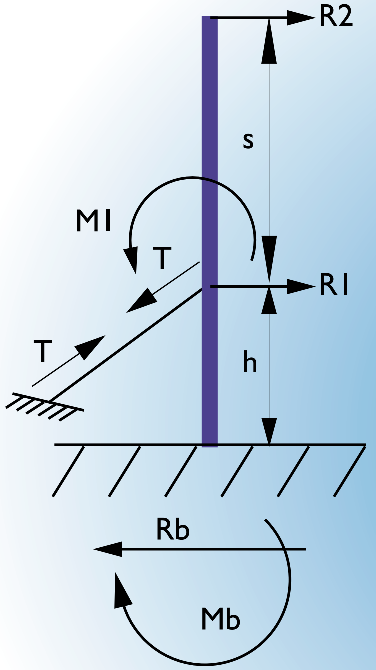
w'(b)=0

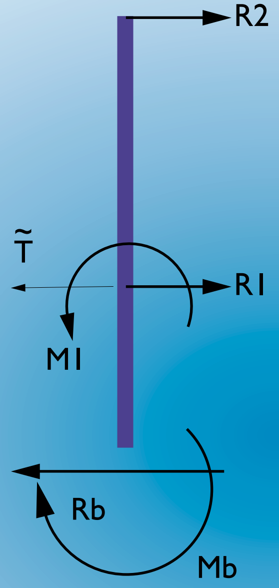
w(b)=0

w(b-s)=0

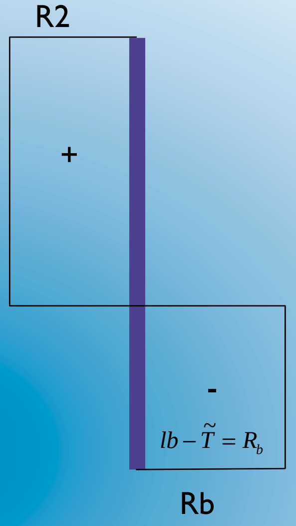
$$\boxed{R_2 = \frac{l}{8s}\left[6b^2 - 4bs + s^2\right]}$$

STUB-MAST STRUCTURAL LOADS





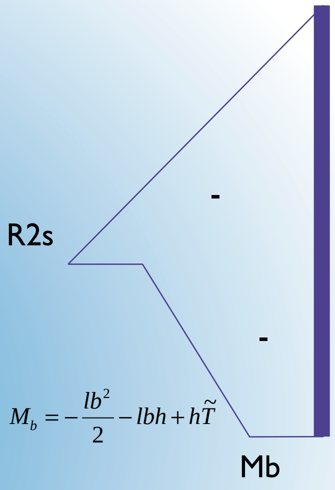
Forces



$$lb-\tilde{T}=R_b$$

$$V=R_2+\left(R_1-\tilde{T}\right)\langle x-s\rangle^0$$

Shear



$$M_b=-\frac{lb^2}{2}-lbh+h\tilde{T}$$

$$M=-R_2x-\left(R_1-\tilde{T}\right)\langle x-s\rangle+M_1\langle x-s\rangle^0$$

Moments

$$EIw''=-M=R_2x+\left(R_1-\tilde{T}\right)\langle x-s\rangle-M_1\langle x-s\rangle^0$$

$$EIw'=\frac{R_2x^2}{2}+\left(R_1-\tilde{T}\right)\frac{\langle x-s\rangle^2}{2}-M_1\langle x-s\rangle+c_1$$

$$EIw=\frac{R_2x^3}{6}+\left(R_1-\tilde{T}\right)\frac{\langle x-s\rangle^3}{6}-M_1\frac{\langle x-s\rangle^2}{2}+c_1x+c_2$$

Evaluate B.C's:

$w'(s+h)=0$

$w(s+h)=0$

$w(s)=\delta_{cable}$

$$w\big|_{x=s}=\frac{1}{EI}\left(\frac{h^2\left[3lb^2+4lbh-4h\tilde{T}\right]}{12}\right)=\tilde{\delta}_{cable}$$

$$\tilde{\delta}_{cable}=\frac{\tilde{T}L}{AE}$$

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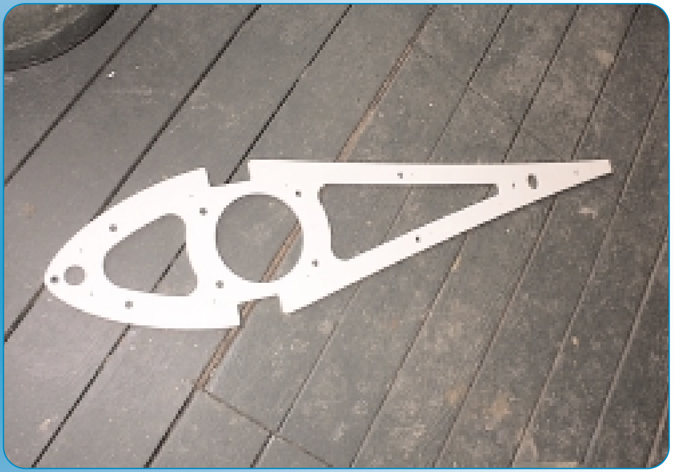
WINGSAIL CONSTRUCTION (1.2)

- Stub mast is a 4” O.D. aluminum T6061 pipe with 3/8” wall thickness

- Wing ribs were routed out of 3/8” marine plywood

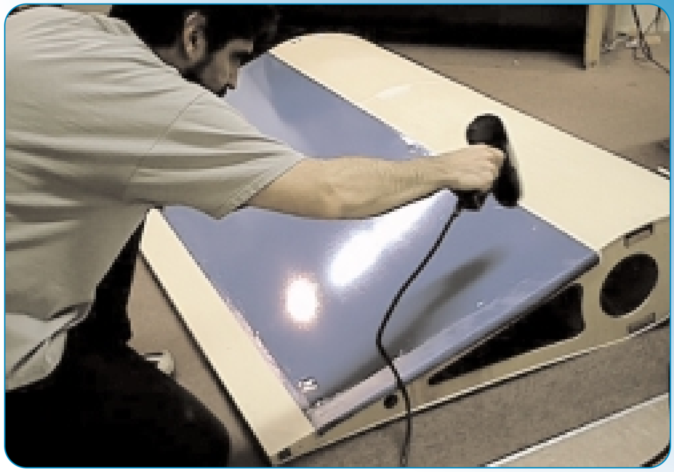


- Ribs assembled on jig, with a spruce spar epoxied in place

WINGSAIL CONSTRUCTION (2.2)

- Skin bonded to ribs with epoxy forming the front of the "D" tube

- Shear webs are made of 3/8" marine plywood



- Wingsail is covered with "industrial" grade mylar covering

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CONSTRUCTION: LOAD TEST

- Load test consisted on hanging a 72 kg. dummy load off the end of the wing, while having the crossbeam of the catamaran secured to a column.

- Based on results of load test, bottom section shear webs were reinforced.

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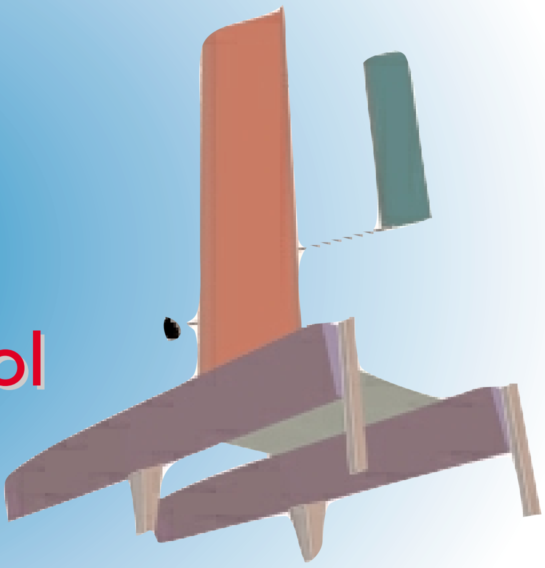
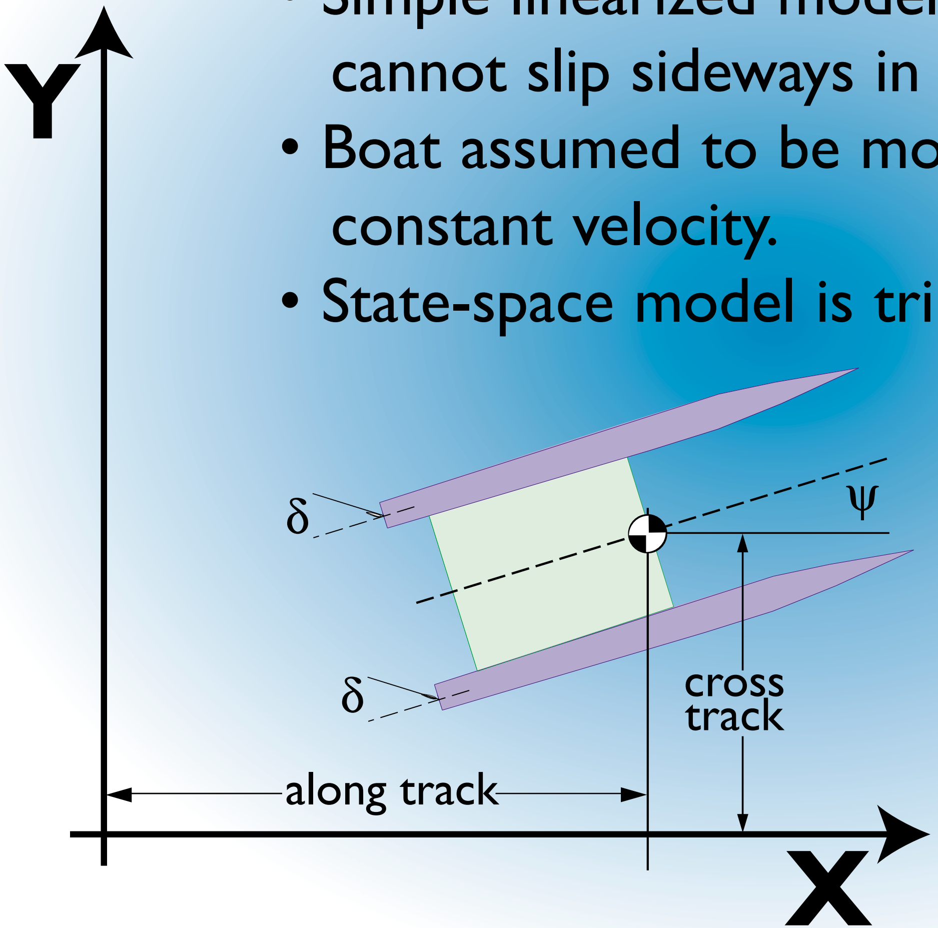


BASIC KINEMATIC MODEL

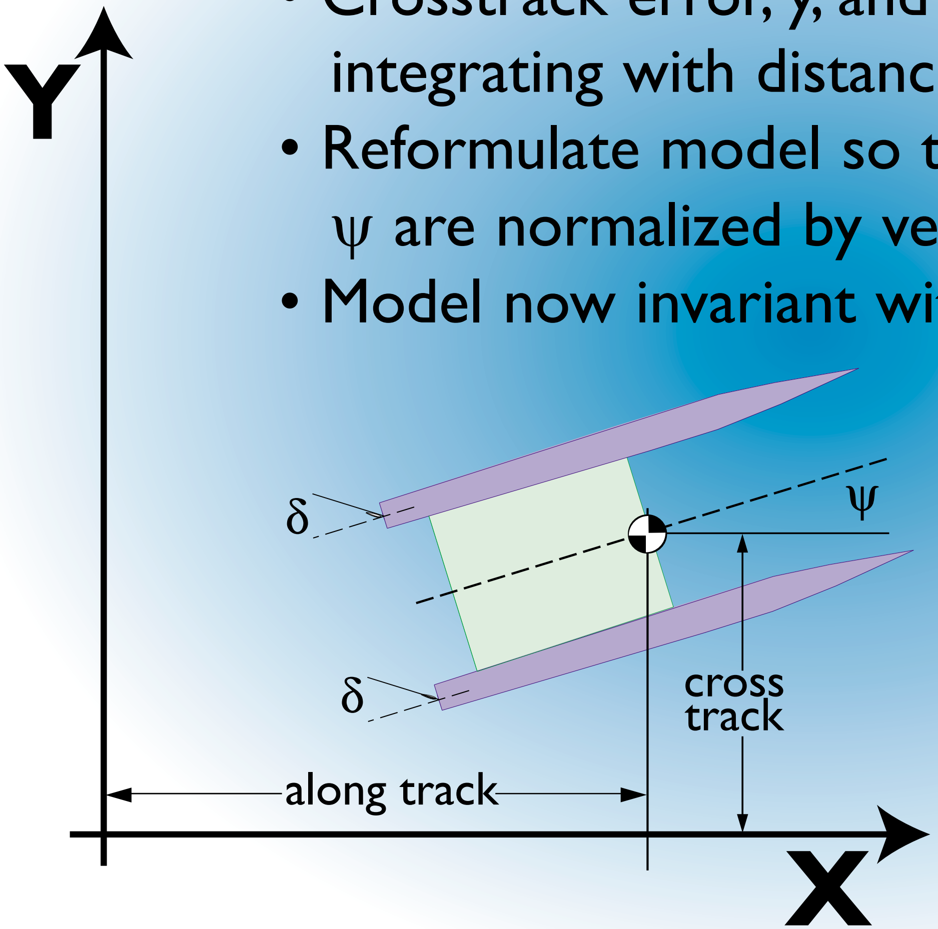
- Simple linearized model assumes that rudder cannot slip sideways in water.
- Boat assumed to be moving along X-axis at constant velocity.
- State-space model is triple integrator.



$$\overset{\bullet}{\begin{bmatrix} y \\ \psi \\ \delta \end{bmatrix}} = \begin{bmatrix} 0 & V_x & 0 \\ 0 & 0 & \frac{V_x}{L} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} y \\ \psi \\ \delta \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u$$

VELOCITY INVARIANCE

- Crosstrack error, y, and azimuth error, ψ, are integrating with distance, not time.
- Reformulate model so that the states for y and ψ are normalized by velocity.
- Model now invariant with velocity.



$$\overset{\bullet}{\begin{bmatrix}\tilde{y}\\ \tilde{\psi}\\ \delta\end{bmatrix}} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & \frac{1}{L}\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\tilde{y}\\ \tilde{\psi}\\ \delta\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1\end{bmatrix}u$$

$$\tilde{y} = \frac{y}{V_x}$$

$$\tilde{\psi} = \frac{\psi}{V_x}$$

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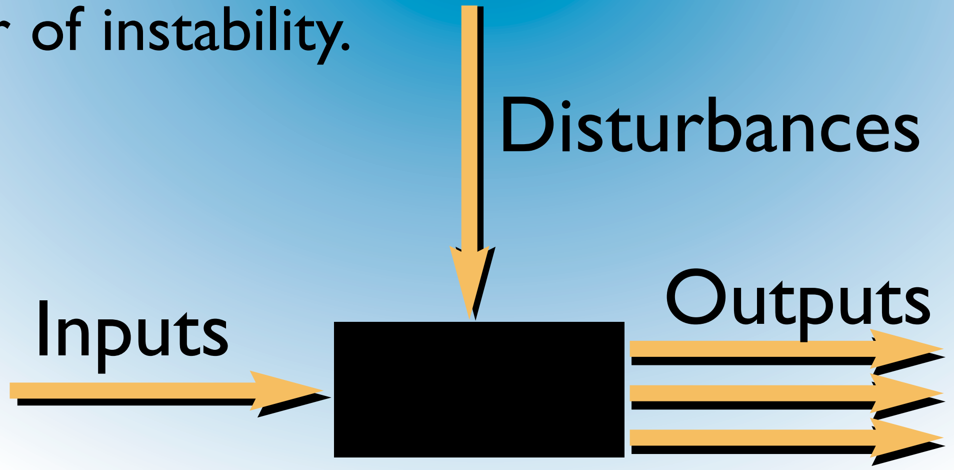
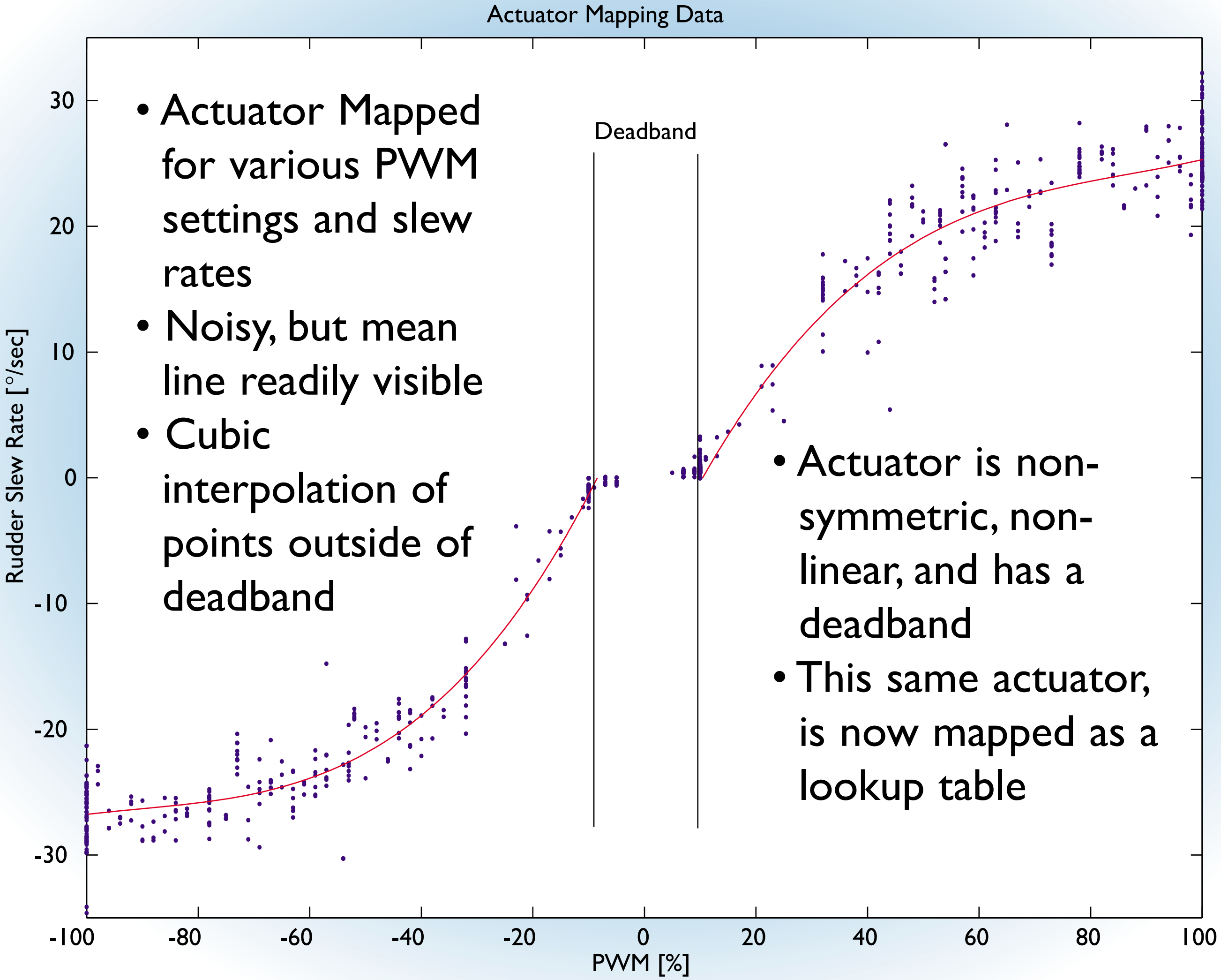
SYSTEM IDENTIFICATION

- Replace the "black box" with a mathematical model.
- Observer Kalman-filter Identification (OKID) method requires only input-output data, no *a priori* knowledge of plant structure is needed.
- Using an identified "high-fidelity" model, greater control system authority can be used without the danger of instability.



NON-LINEAR ACTUATOR MAPPING

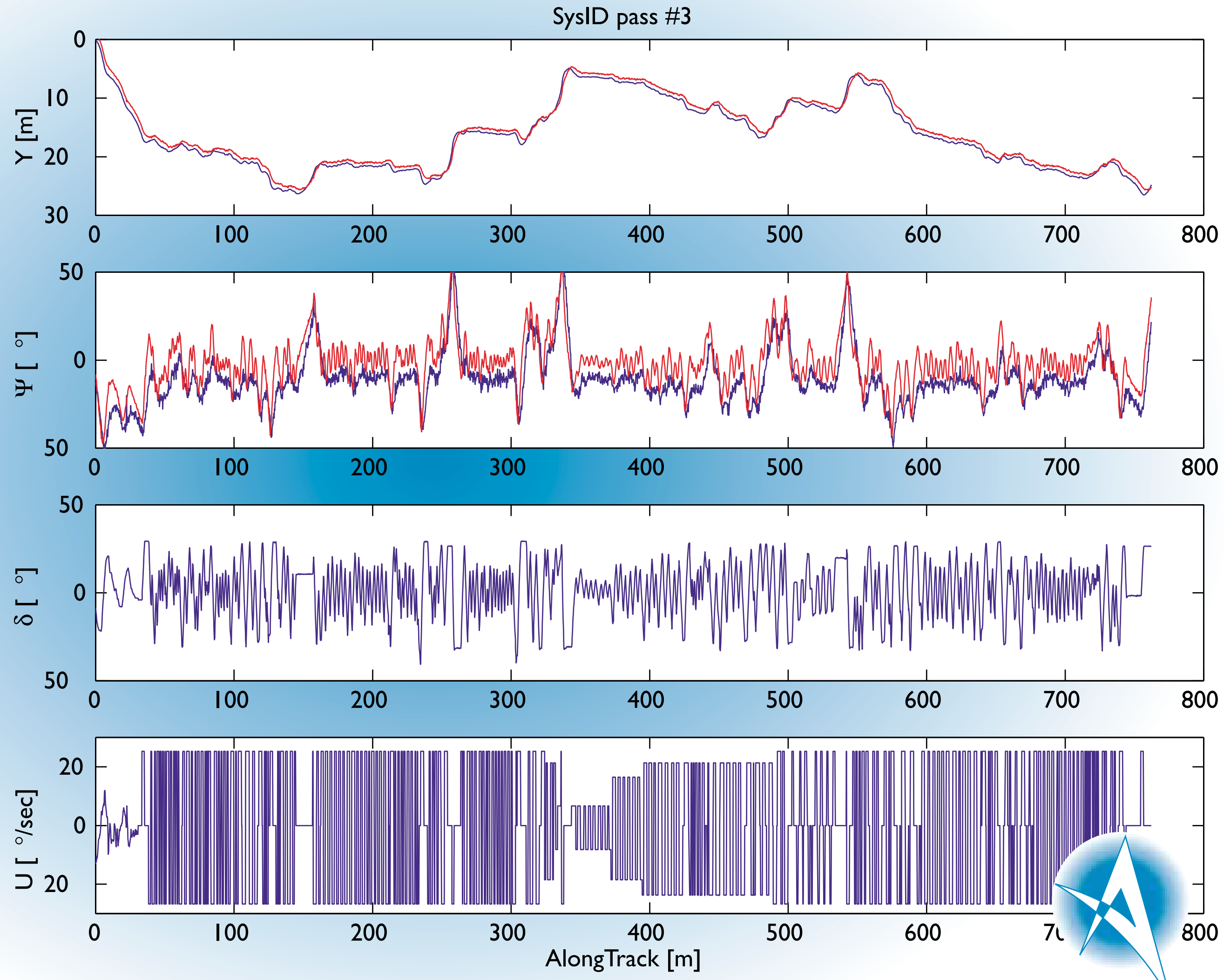


- Actuator Mapped for various PWM settings and slew rates
- Noisy, but mean line readily visible
- Cubic interpolation of points outside of deadband

- Actuator is non-symmetric, non-linear, and has a deadband
- This same actuator, is now mapped as a lookup table

TYPICAL SYS ID PASS

- Rudder was slewed by human pilot to excite all modes of sailboat.
- Both GPS-derived bearing and azimuth from attitude system are shown.
- Sensors were sampled at 100 Hz.



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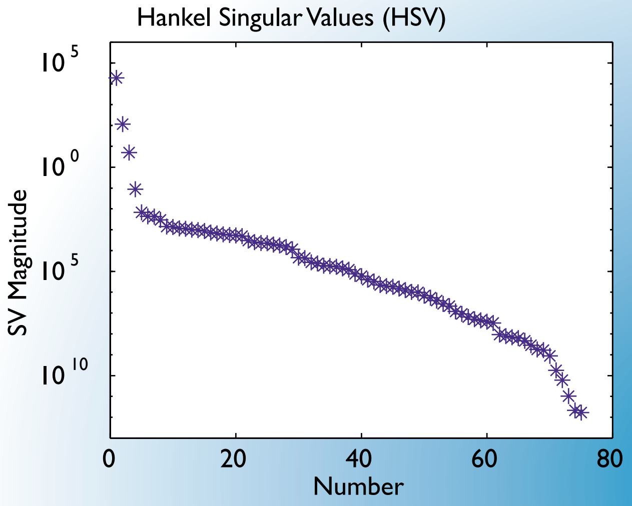
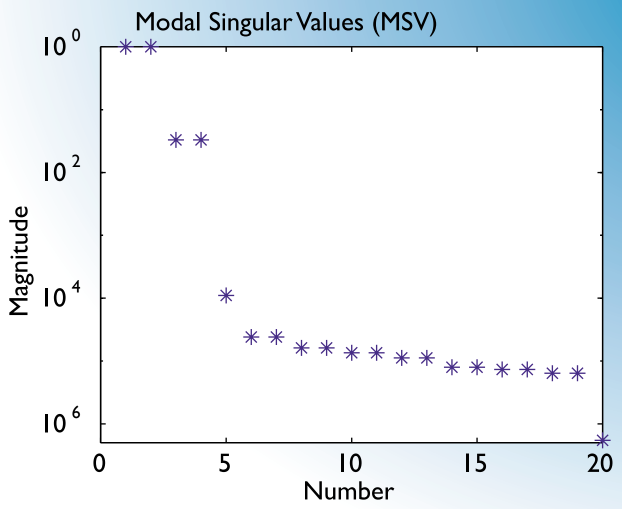
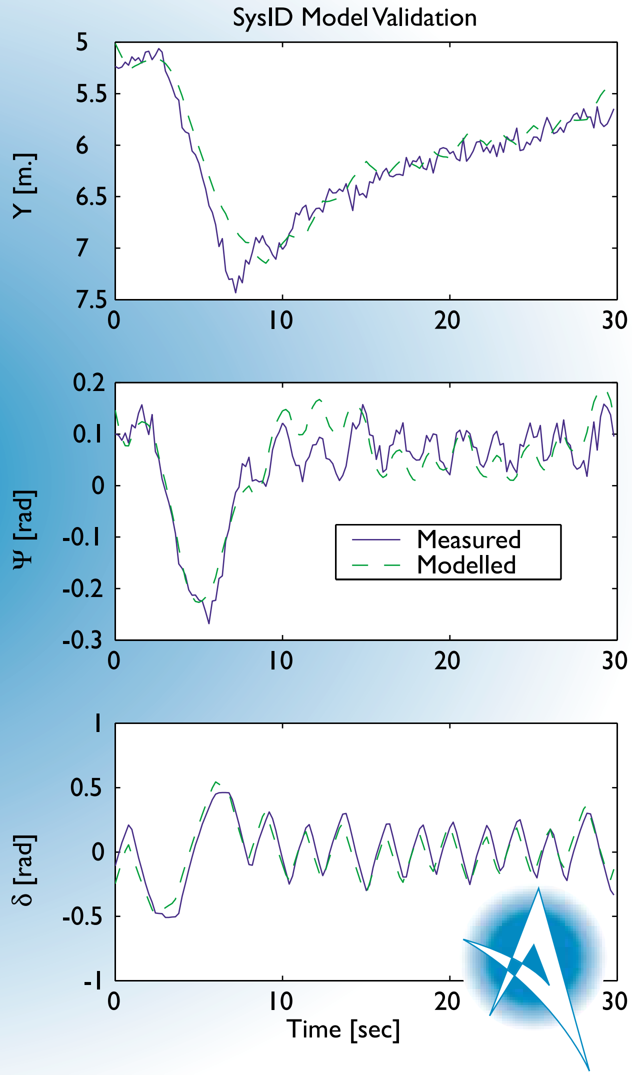
OKID RESULTS





- Large drop off in singular values after 4th order.
- Modal singular values confirm 4th order model.
- Reconstruction of data from a different data set shows excellent agreement with measurements.



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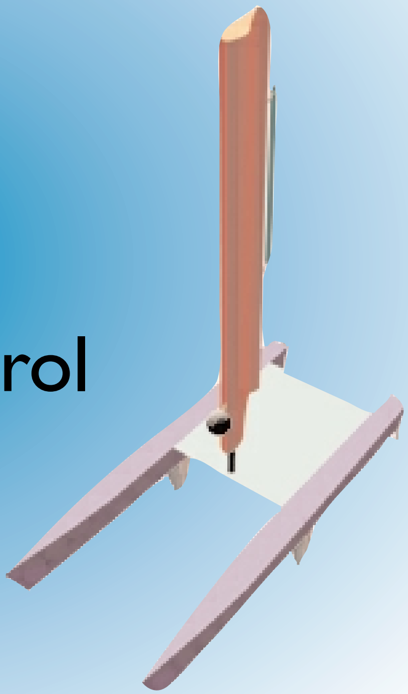

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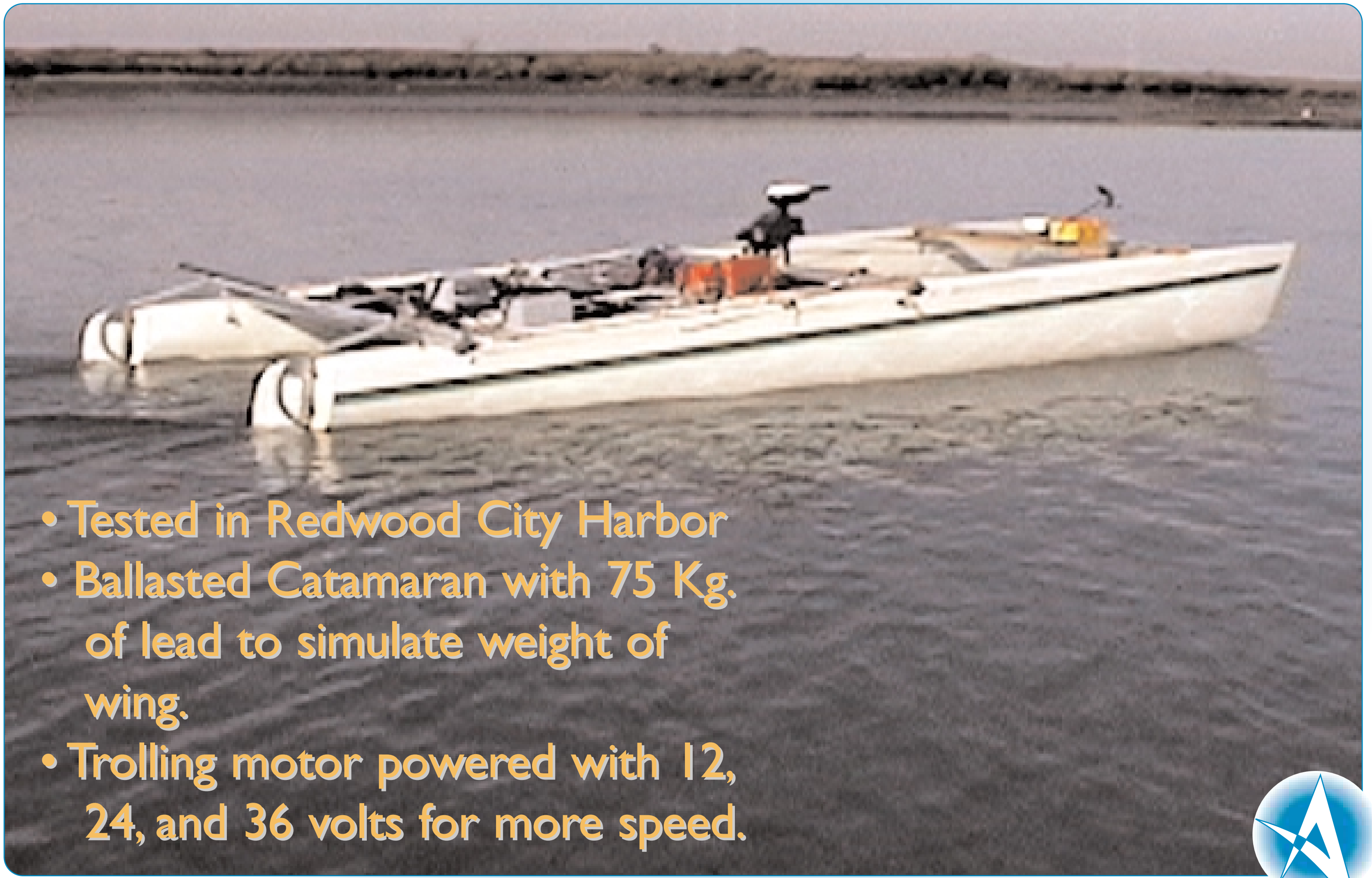
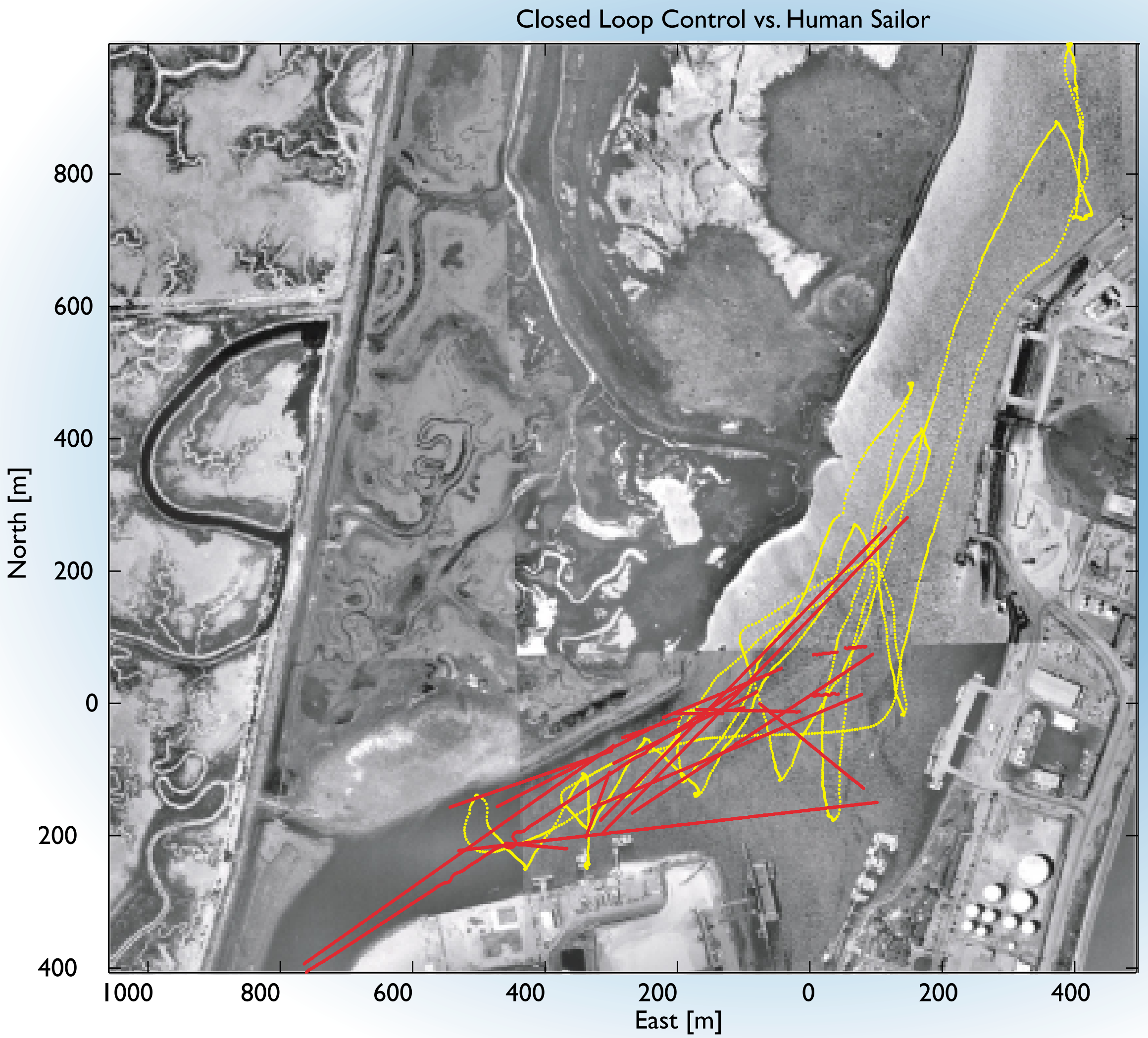
TROLLING TEST SETUP



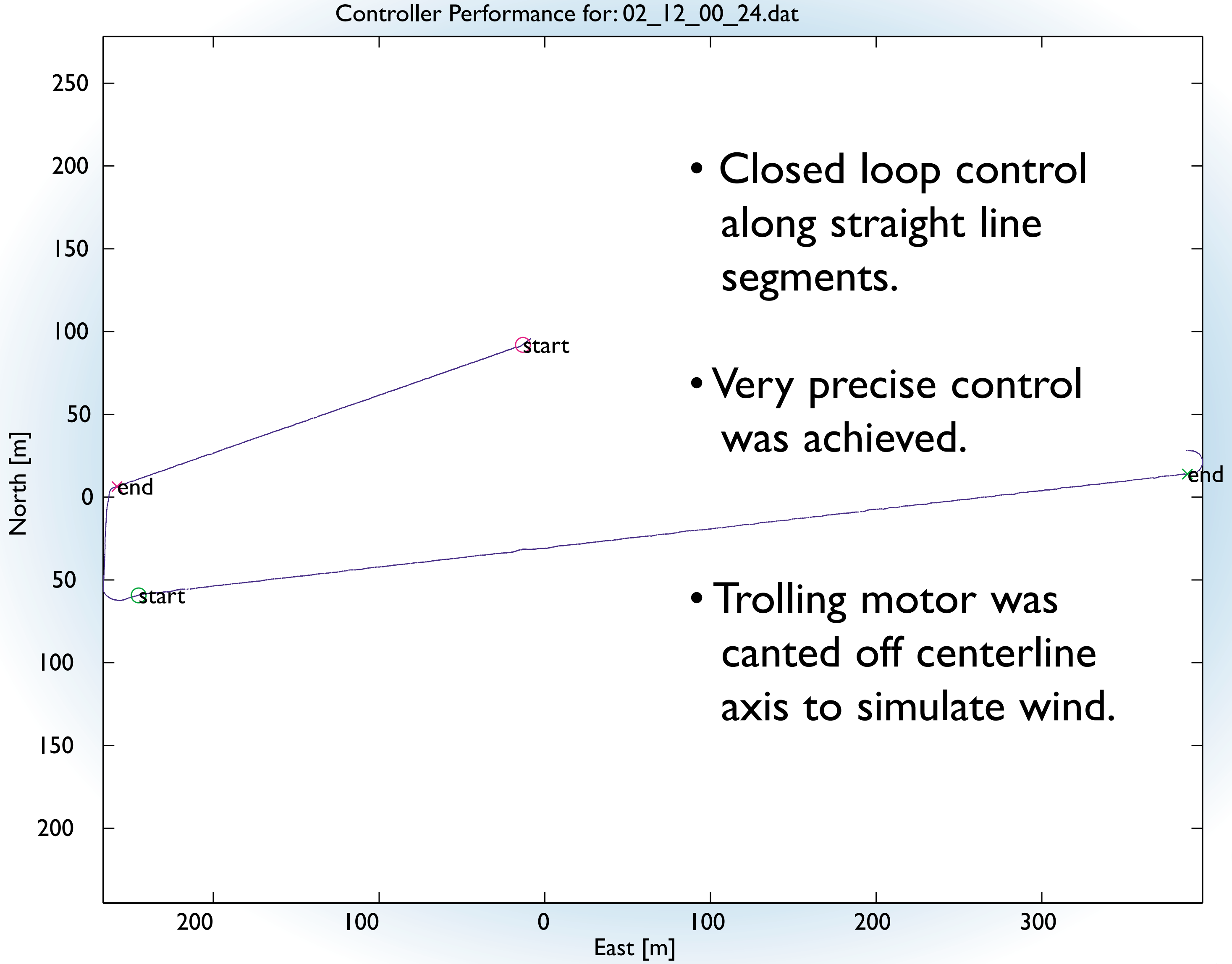
- Tested in Redwood City Harbor
- Ballasted Catamaran with 75 Kg. of lead to simulate weight of wing.
- Trolling motor powered with 12, 24, and 36 volts for more speed.

BIRD'S EYE VIEW OF TROLLING DATA



- Data from sailing and trolling in Redwood city harbor, taken over a year apart.
- Human sailing data shown in yellow.
- Computer data shown in red.

BIRD’S EYE VIEW OF CLOSED-LOOP



- Closed loop control along straight line segments.
- Very precise control was achieved.
- Trolling motor was canted off centerline axis to simulate wind.

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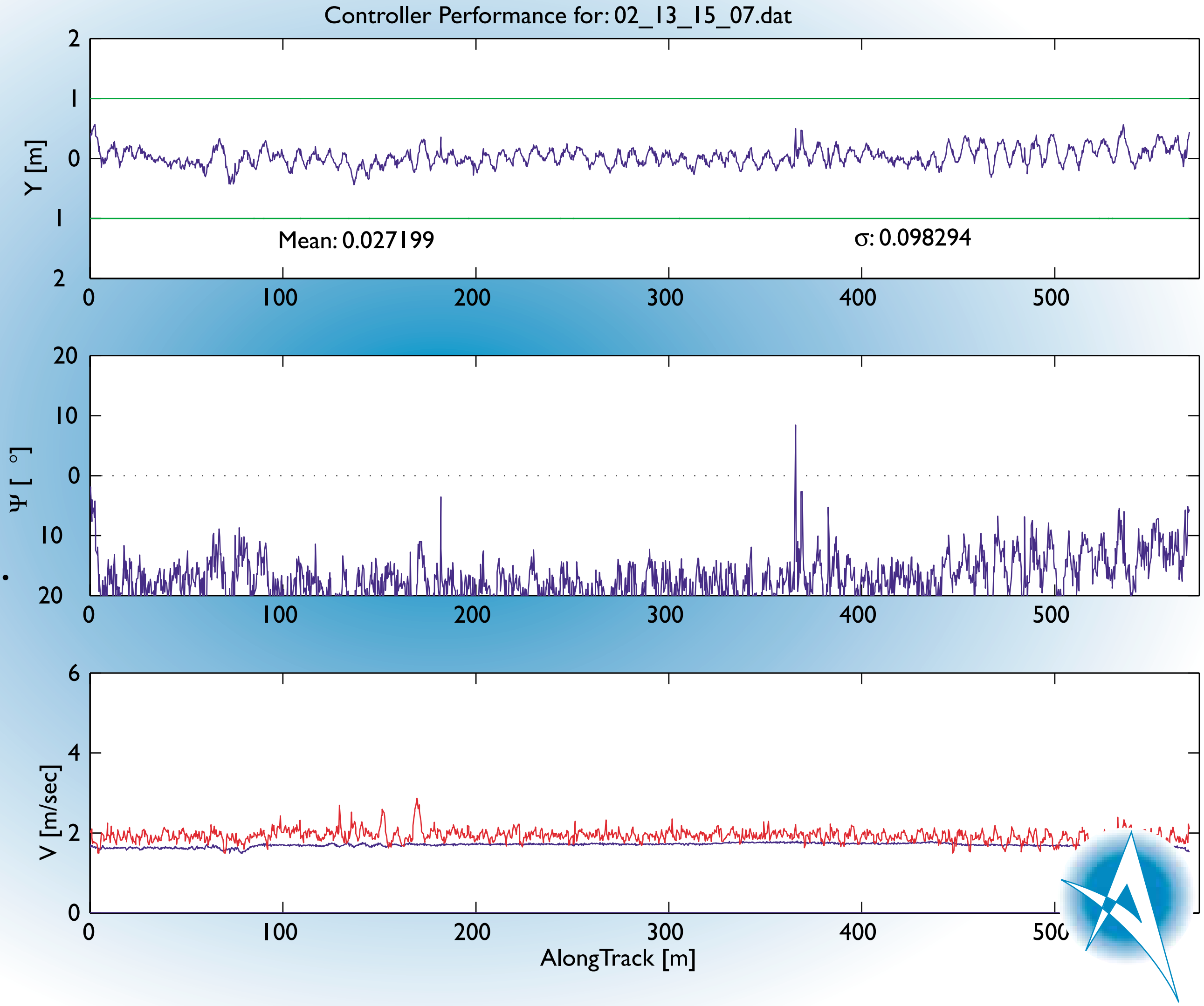
TROLLING MOTOR CONTROL (1.2)

- Close-up view of first pass.
- OKID 4th order, vel. invariant controller.
- Mean: 0.03 m., Standard Deviation: 0.10 m.
- Note bias in Azimuth due to current.
- Boat Speed 4 kts.



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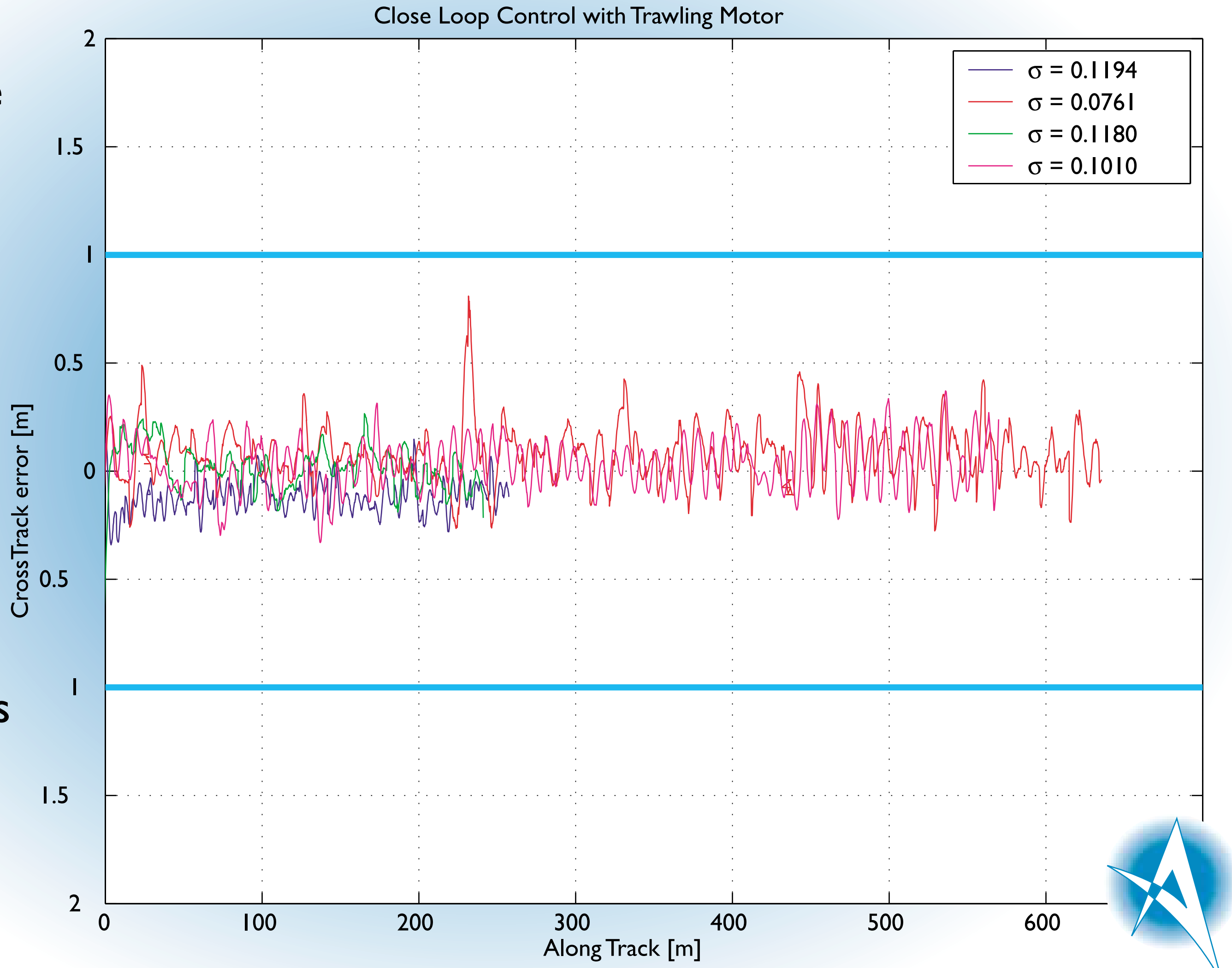
TROLLING MOTOR CONTROL (2.2)

- All passes have standard deviations below 0.15 meters.
- All means are below 0.15 meters.
- "Troll" path never exceeds 1 meter from desired path.



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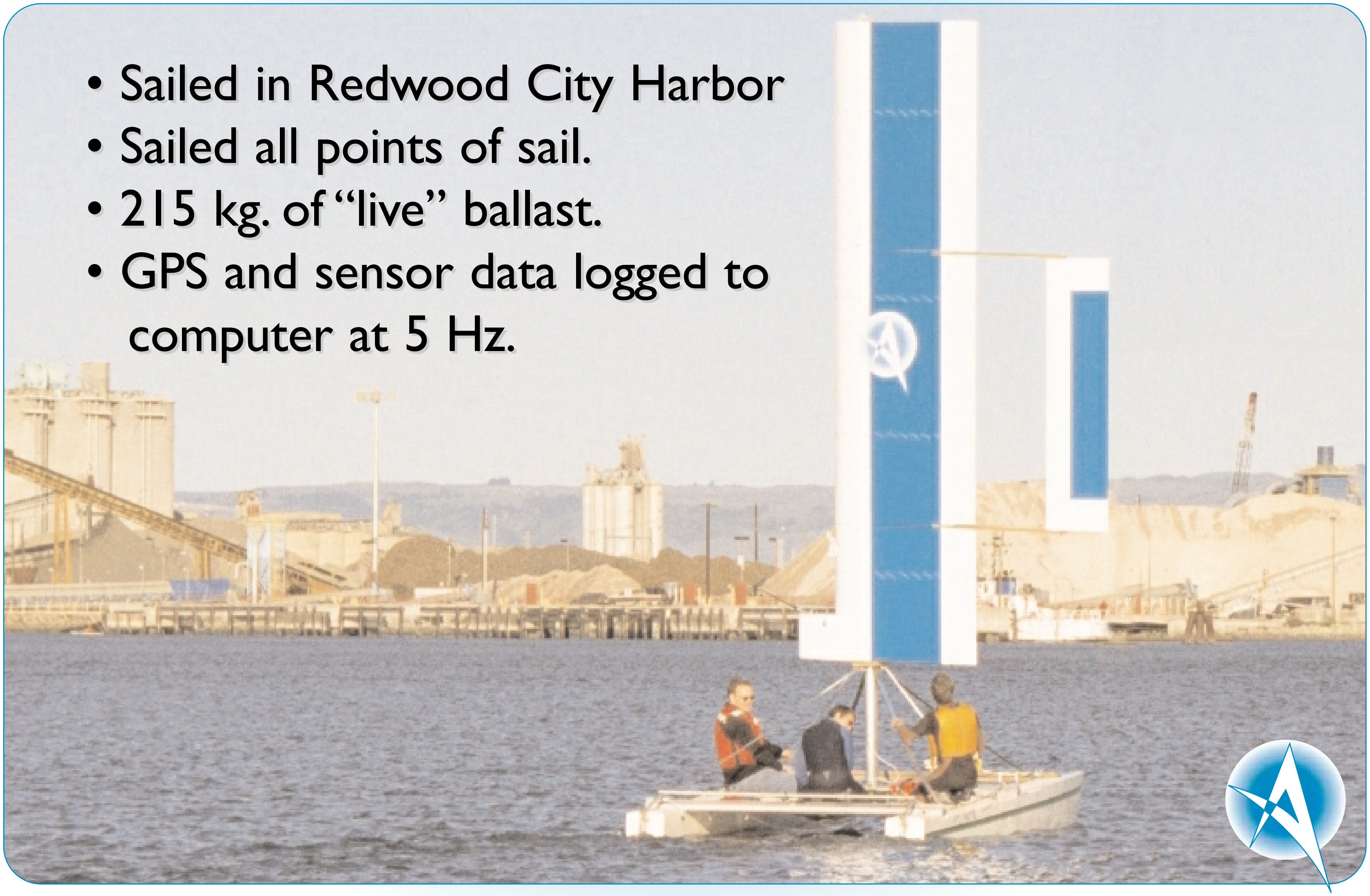
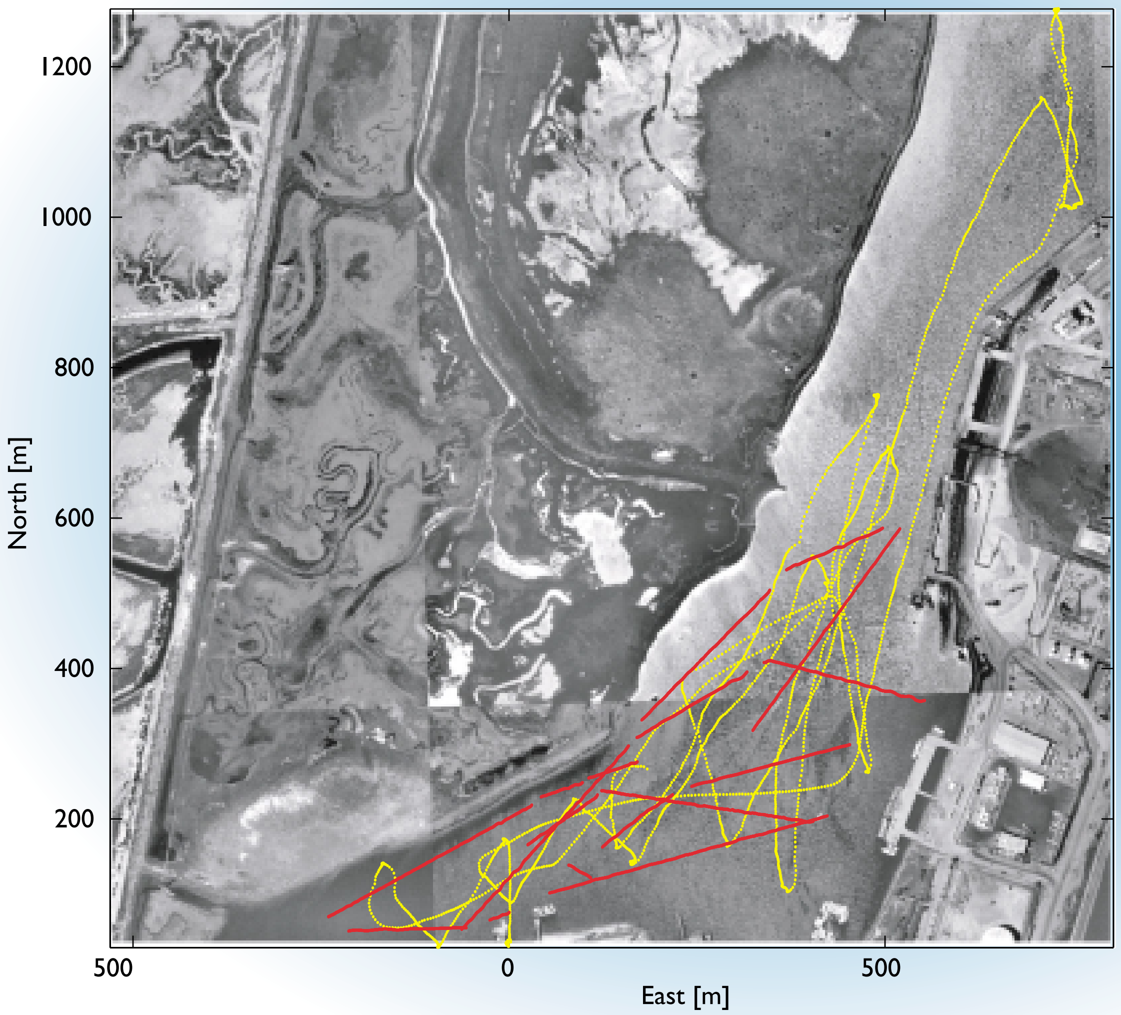
SAILBOAT SETUP



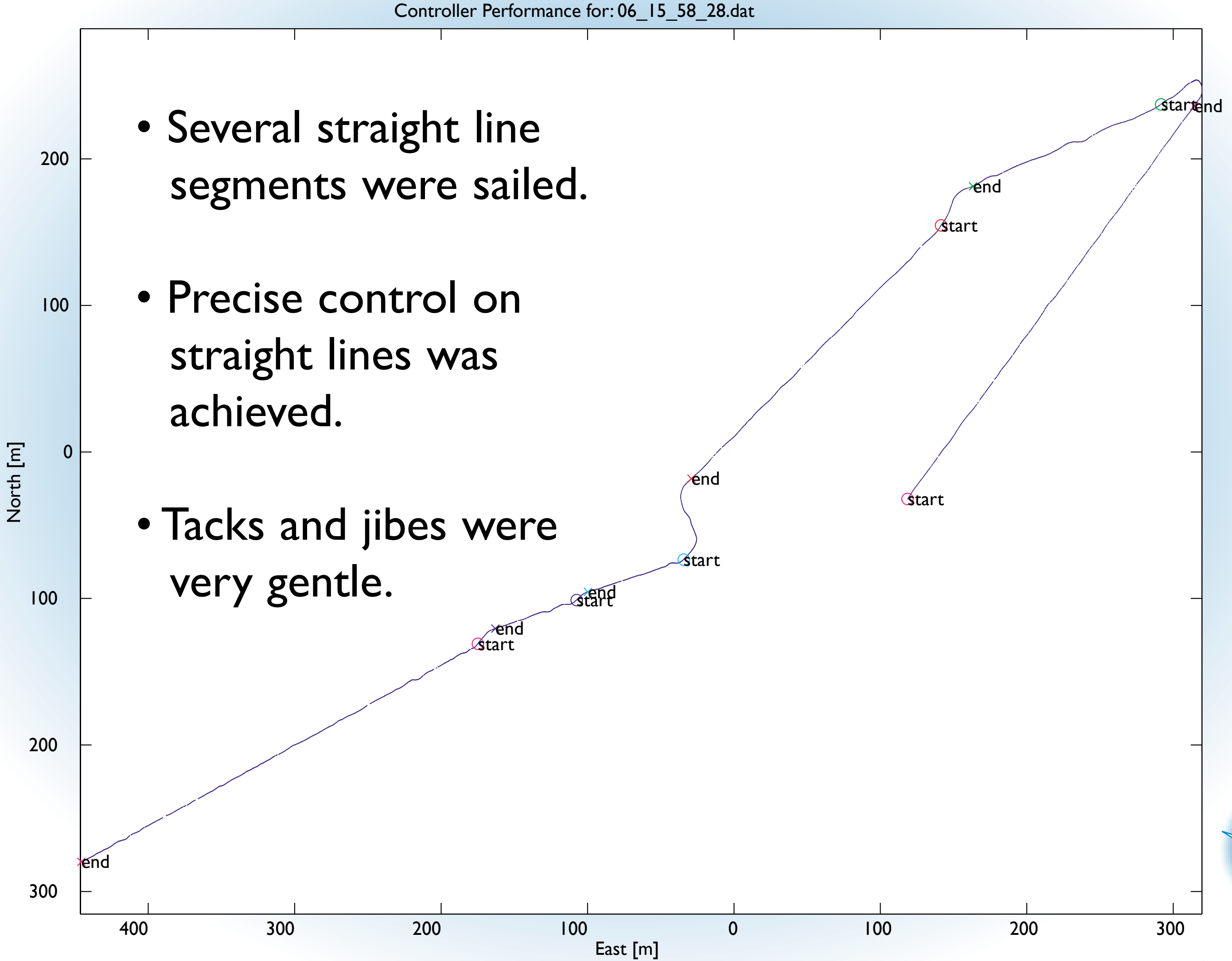
- Sailed in Redwood City Harbor
- Sailed all points of sail.
- 215 kg. of “live” ballast.
- GPS and sensor data logged to computer at 5 Hz.

BIRD'S EYE VIEW OF ALL DATA


Closed Loop Control vs. Human Sailor

- Data from normal sailing and wing-sailing in Redwood City harbor, taken over a year apart.
- Human sailing data shown in yellow.
- Computer data shown in red.

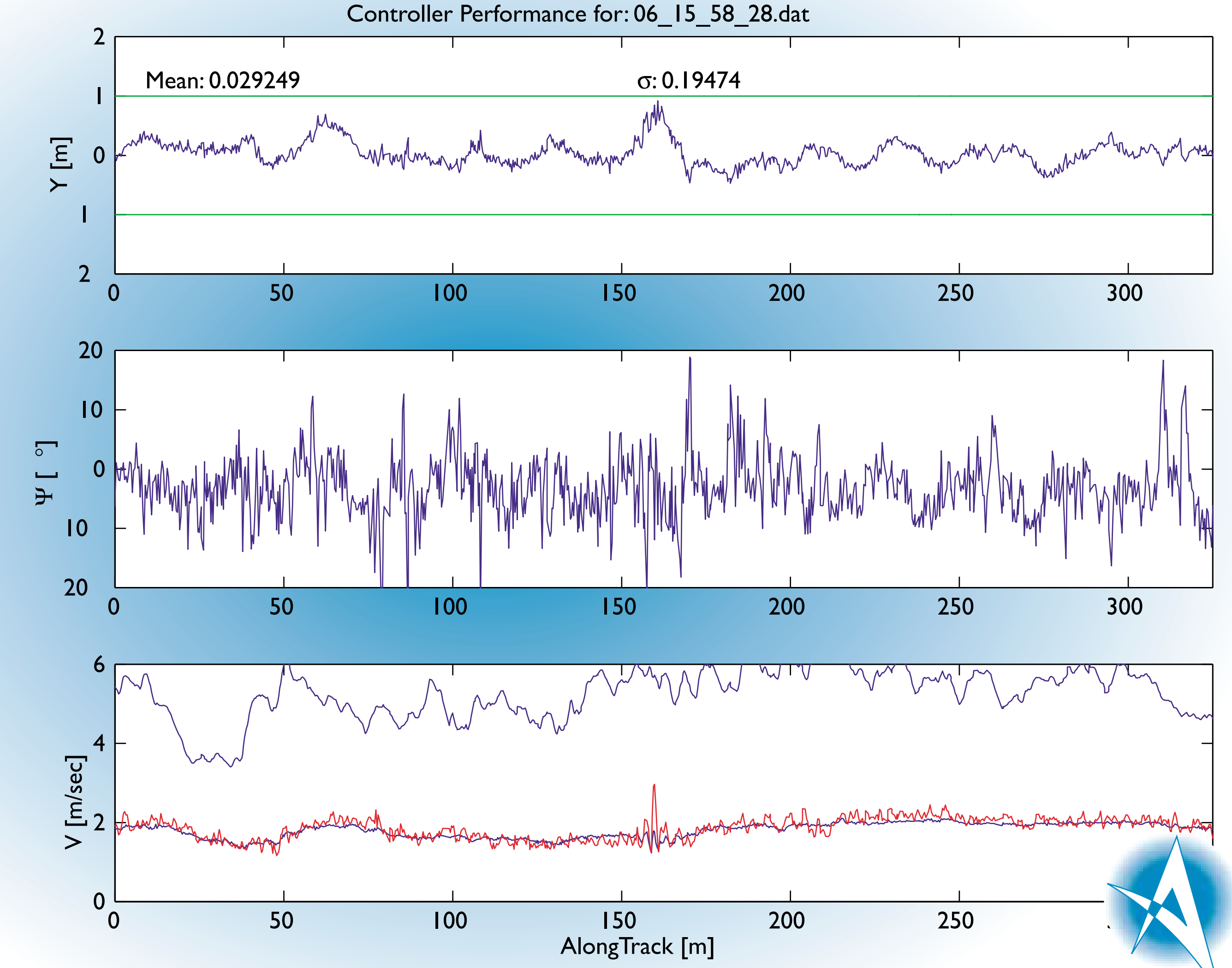
BIRD'S EYE VIEW OF CONTROL


Controller Performance for: 06_15_58_28.dat

- Several straight line segments were sailed.
- Precise control on straight lines was achieved.
- Tacks and jibes were very gentle.

CLOSE-UP OF SAILING CONTROL (1.2)

- Close-up view of first pass.
- OKID 4th order, velocity invariant controller.
- Mean: 0.03 m., Standard Deviation: 0.20 m.
- Wind 8-12 kts.
- Boat speed 4-5 knots.



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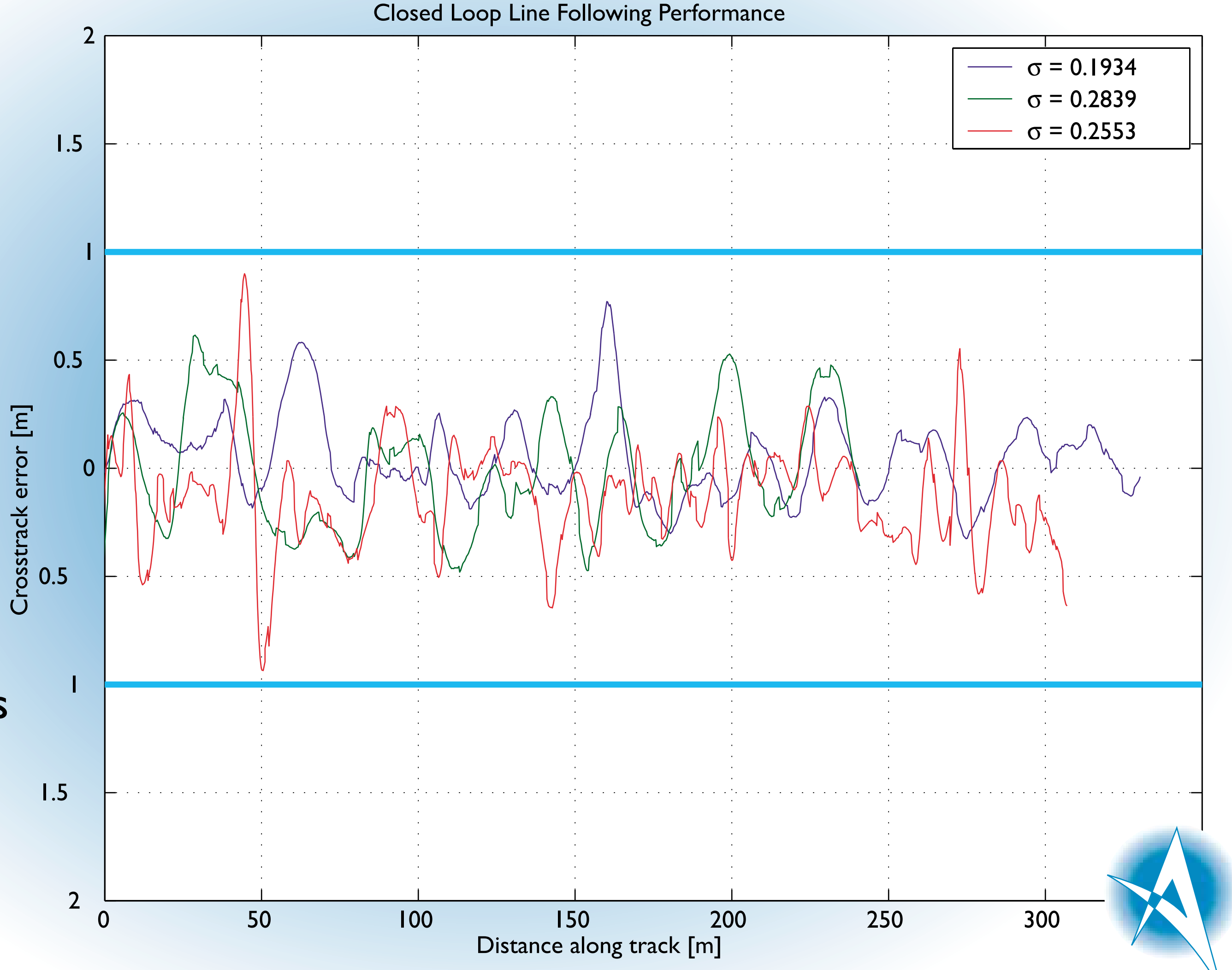
CLOSE-UP OF SAILING CONTROL (2.2)

- All passes have standard deviations below 0.3 meters.
- All means are below 0.2 meters.
- “Sail” path never exceeds 1 meter from desired path.



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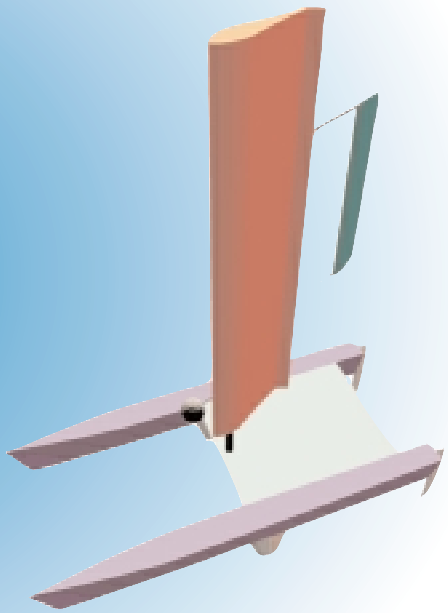

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CONCLUSIONS (1.2)

- Experimentally demonstrated precise control of an autonomous sailboat to better than 0.3 meters.
- Identified a robust plant model and controller for autonomous sailboat that is invariant under velocity changes.
- Developed optimized symmetric wingsail section based on requirements unique to sailing vehicles.
- Developed and experimentally demonstrated novel quaternion-based attitude estimation from vector observations.
- Developed and experimentally demonstrated novel method for calibrating strap-down 3-axis magnetometer that requires no external reference.

CONCLUSIONS (2.2)

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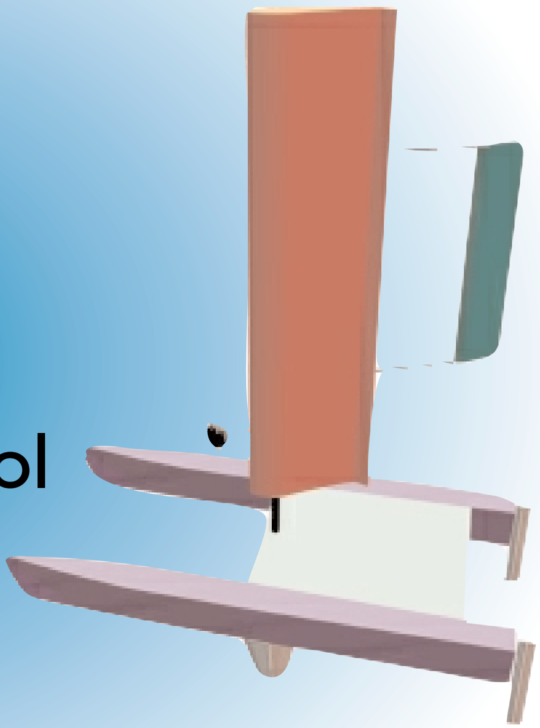

FUTURE WORK (1.2)

- Implement Auto-Tacking and -Jibing.
- Implement reverse controller and station keeping.
- Optimal trajectories to destination.
- On-the-fly current estimation.
- Map/Gradient based higher level navigation.
- Implement distributed control system.

FUTURE WORK (2.2)

- Experimentally determine actual WingSail performance.
- Improve WingSail structural robustness.
- Improve user interface, and control software.
- Implement Real-Time-OS.
- Solar panels or wind turbine for on-board power generation.
- Unmanned sail to Honolulu?

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- Testing crews: Konstantine, Lee, Chad, Jaewoo, J.Fey, Demoz, Sharon, Sherman, James, Eric, Lude, Guttorm, Rob.
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- All the labs that unknowingly donated material to the project in the middle of the night.