

INSPIRE: Mobile-manipulating UAVs for Sensor Installation, Bridge Inspection and Maintenance



Paul Y. Oh –University of Nevada, Las Vegas (UNLV)

Missouri Science and Technology (MS&T) Annual Meeting

Rolla, MO, August 14, 2018

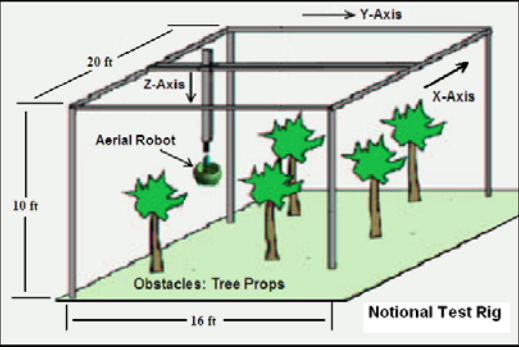
History: Continuum of Research

2000 – 2011: UAVs

- NASA JPL: Perch-and-Stare
- NSF CAREER: **Fly indoors**
- DARPA OAV – Army FCS
- Caves (**Hovering Airplane**)
- UAV-UGV Coordination (**Transport**)
- Pilot Training (**Chase View**)

Sept. 11, 2001

Hurricane Katrina

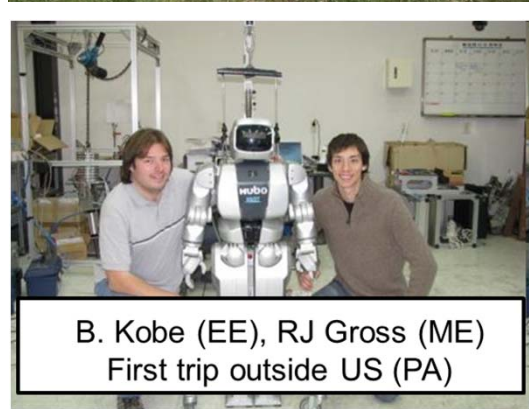


Boeing Welliver

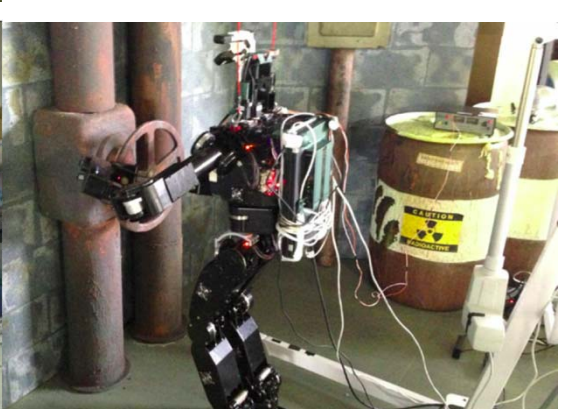


2007 – 2012: UAVs & Humanoids

- Boeing - Globalization
- NSF PIRE (**Humanoids** International)
- NSF MRI (7 Hubos to US schools)
- NSF CRI: **UAVs with Limbs** (MM-UAV)



B. Kobe (EE), RJ Gross (ME)
First trip outside US (PA)



2008 – 2014: Manipulation

- UAVs and Manipulation (peg-in-hole)
- **DARPA Robotics Challenge**
- **UAVs and valve-turning**

Hi-DOF General Purpose Robots: Systems for Tomorrow's "Material-Handling" Needs

Disasters as “Why” ... Shaped my “What” and “How”



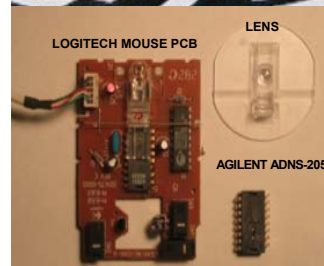
Sept 11, 2001: Amtrak NE Corridor

U.S. Army Telemedicine and
Advanced Technology Center



Near-Earth UAVs

- Degraded Comms
- Poor GPS
- Obstacles
- Dynamic

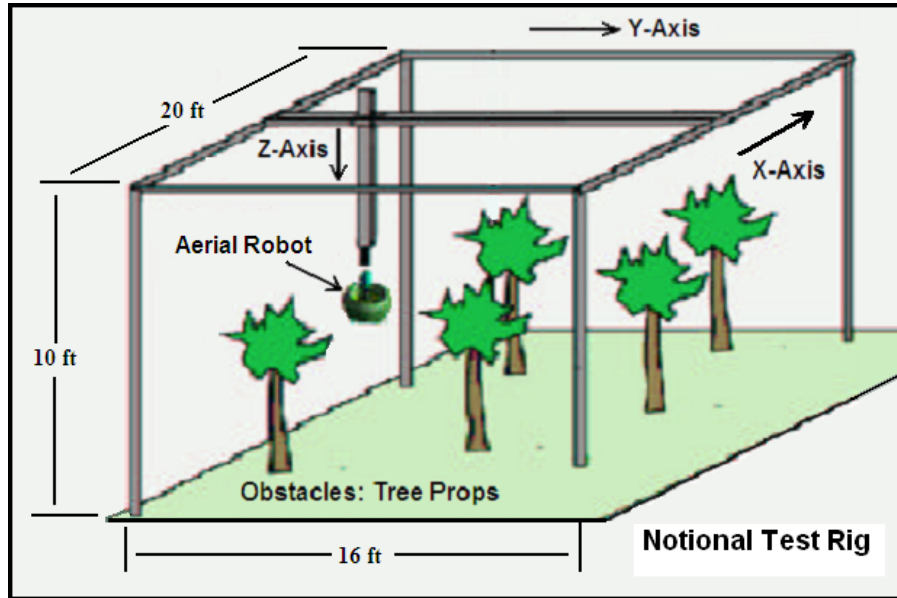


Optic Flow Sensor



Courtesy: Geof Barrows, Centeye

Notional Concept



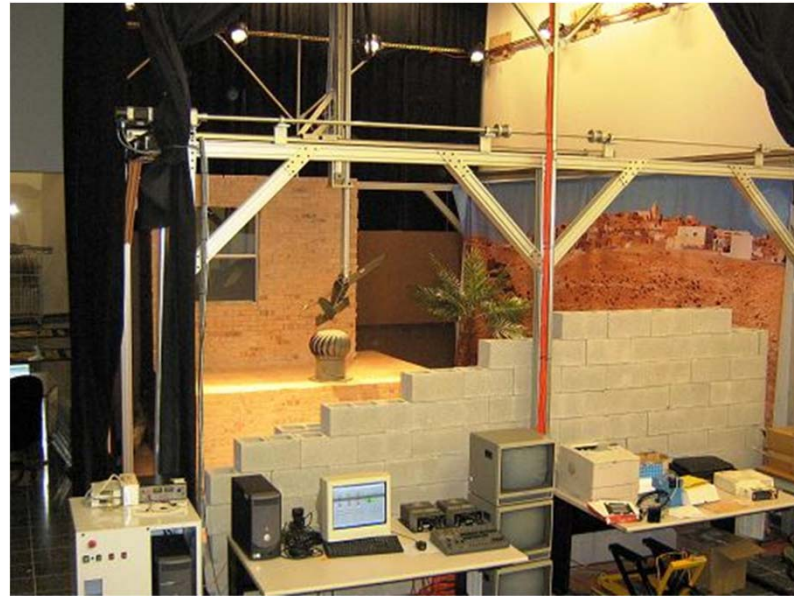
- Gantry + PTR (6-DOF)
- Mockup air vehicle
- Real sensors, time, obstacles
- Hi-fidelity aircraft model

HITL: Test rig moves the aerial robot by mimicking the math model

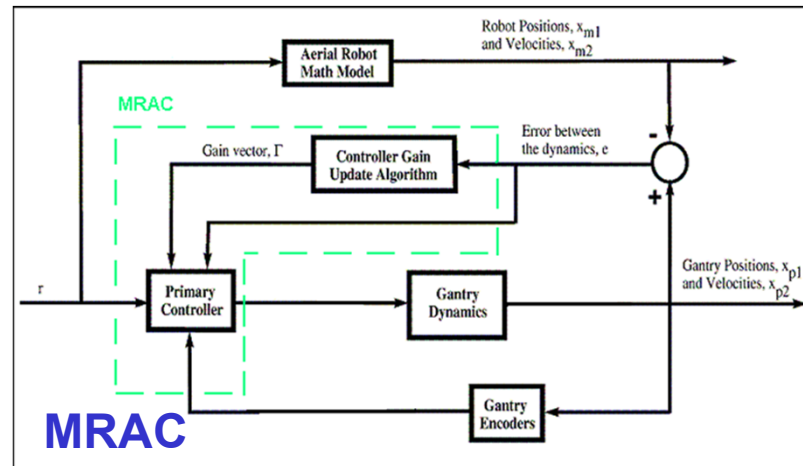
Realization



CAREER
IIS- 0347430



Volume: 25 x 25 x 15 cubic feet



"A Hardware-in-the-Loop Test Rig for Designing Near-Earth Aerial Robotics,"

V. Narli, P.Y. Oh, IEEE ICRA, Orlando FL, pp. 2509 - 2514, May 2006.

New Tools Enable Designing Analytically (2002-2008)



- Search & Rescue Blimp
- 3D Reconstruction Kite



- Indoor flying
- Perch & Stare

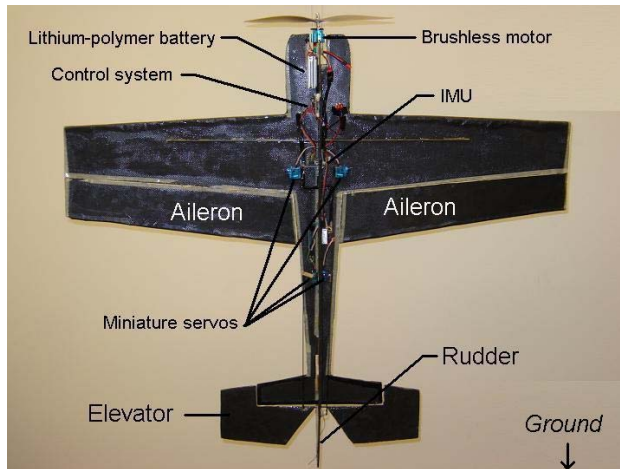


- Autonomous Landing
- Collision Avoidance

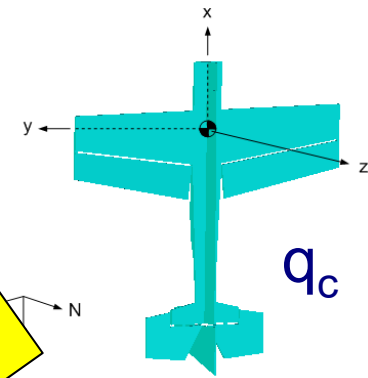


- Hovering Airplane
- UGV-UAV coordination

Solution: Quaternions Enable Cruise-to-Hover and Navigation



- High endurance
- High Maneuverability (“Dash”)
- Hovering Capability



Error
Quaternions

$$e = q_m^{-1} \otimes q_c$$

Control Problem Solved



Green, W.E., Oh, P.Y., [“A Hybrid MAV for Ingress and Egress of Urban Environments”](#), *IEEE Transactions on Robotics*, May 2009

How to Open Doors? Aerial Manipulation?



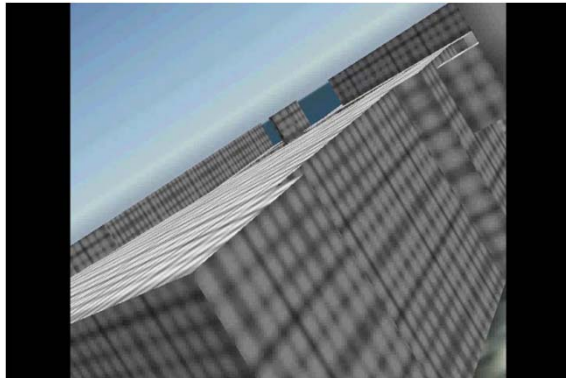
- Buoyancy Envelope
- Quad 500 g payload
- 2 operators
- 3 scissor arms
- Linear actuator
- Roll and Extend



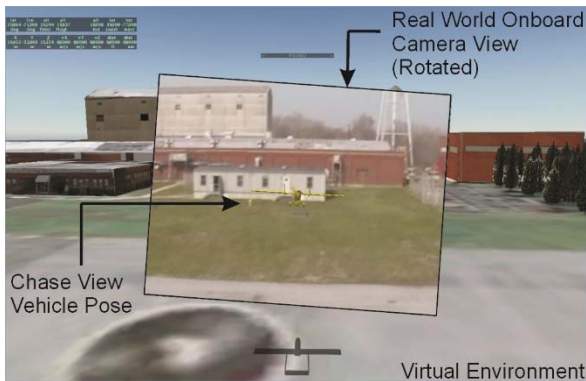
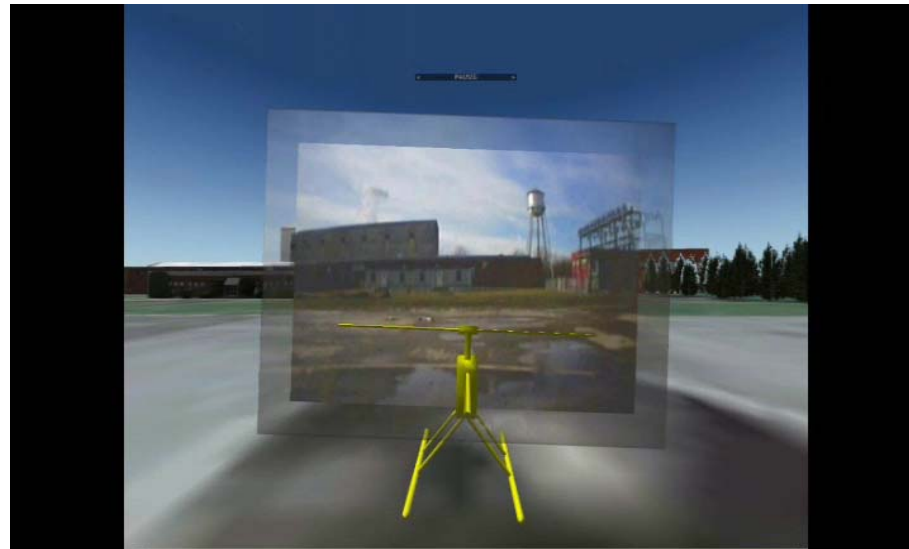
- Payload not key issue
- Perfect LOS and Comms
- 2 operator coordination issue

Korpela, C.M., Danko, T.W., Oh, P.Y., "[Designing a System for Mobile Manipulation from an Unmanned Aerial Vehicle](#)" IEEE TEPPRA, Woburn, MA 2011

Improved Field-of-View: Shared Fate Approach?



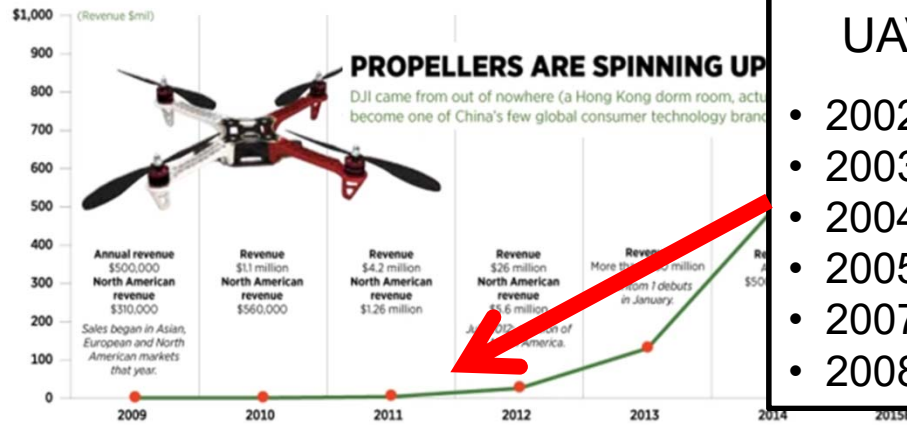
Internal View



Chase View

Hing, J., Sevcik, K., Oh, P.Y., "Improving unmanned aerial vehicle pilot training and operation for flying in cluttered environments", IEEE IROS 2009

Hockey Stick Graph – The Outcome-Based Economy

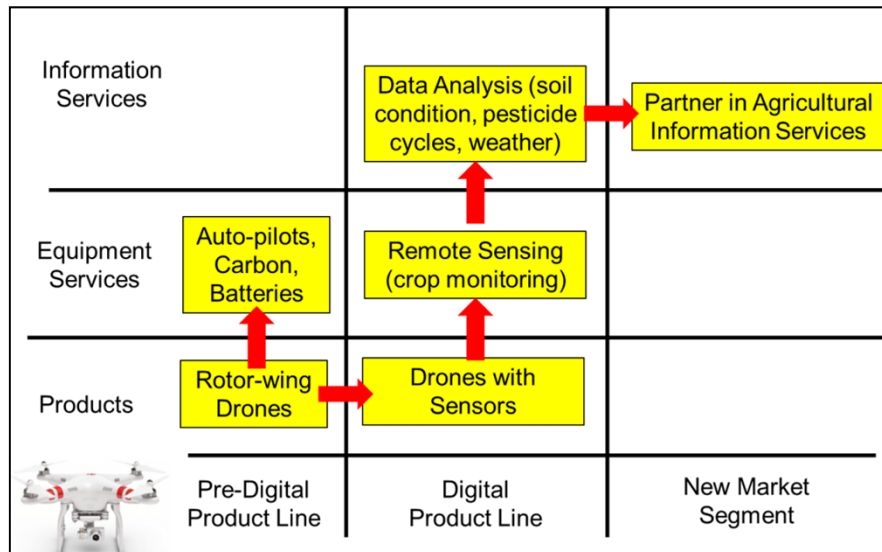


UAV Academics Timeline

- 2002: Collision Avoidance focus
- 2003: LIPO Batteries
- 2004: Carbon Fiber
- 2005: Brushless DC motors
- 2007: Cameras, GPS, IMU
- 2008: Lower-cost LIDAR

Great for 3Ps:

- Proposals
- Publish
- PhDs



Same Issues: Falling...

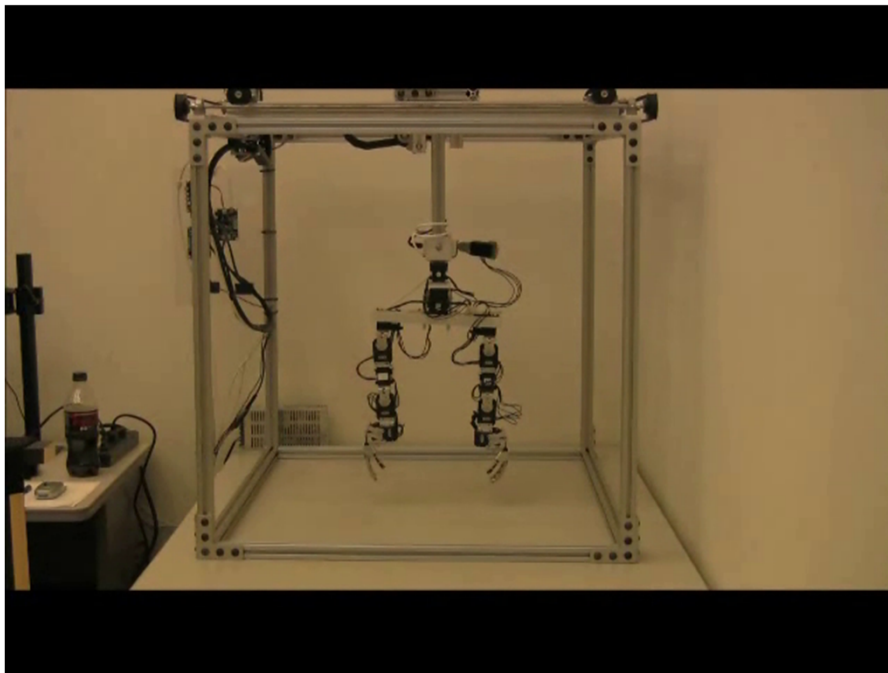
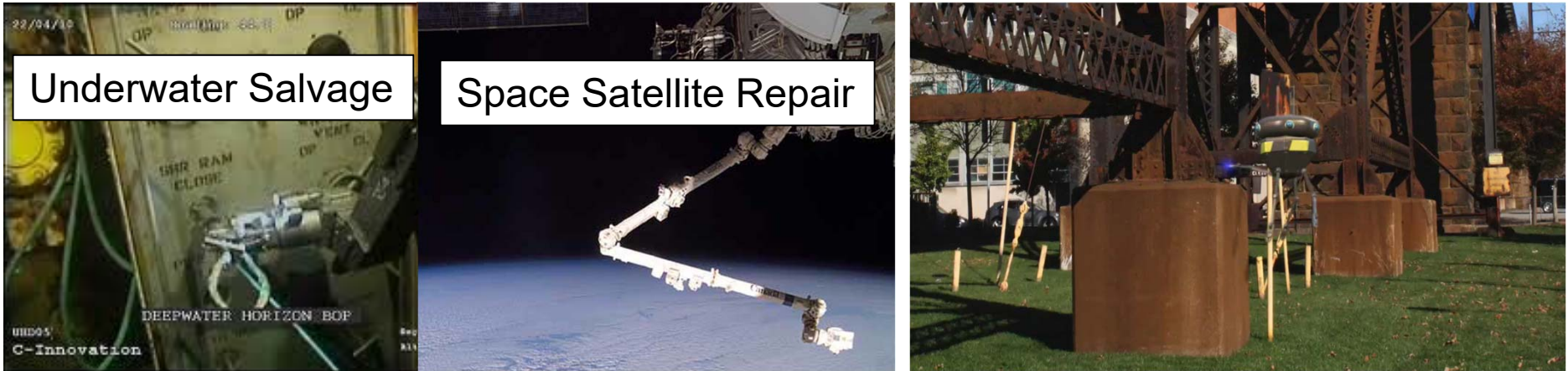
Outcome-Based Economy (workforce development and capacity building)

- Pay-per-outcome
- New connected **ecosystem**
- **Platform** Enabled Marketplace

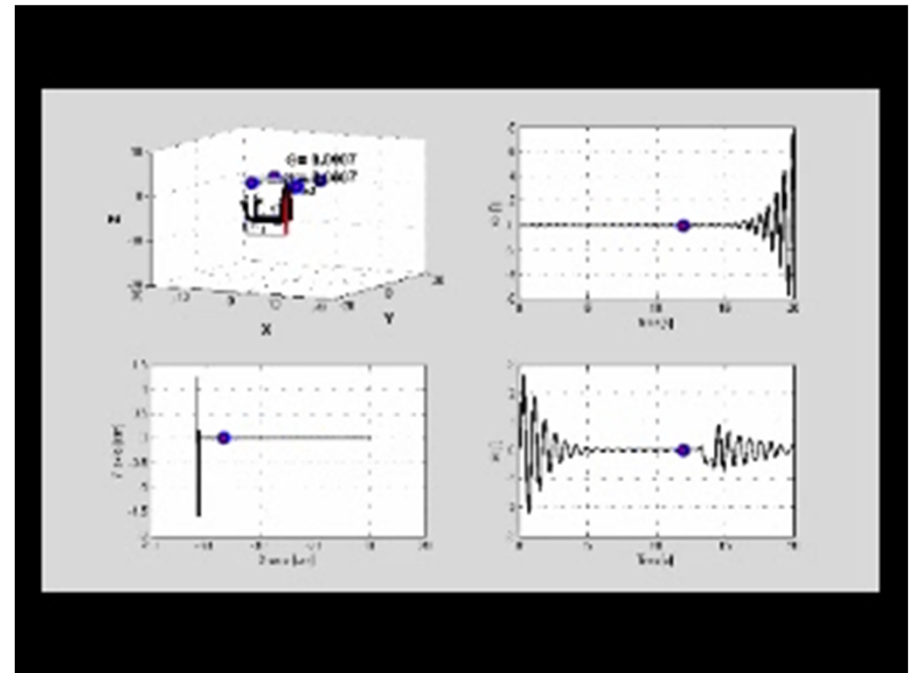


Manipulation Destabilizes

Mobile Manipulating UAVs (MM-UAVs) Concept

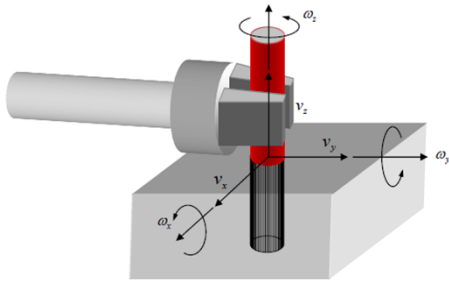


Vehicle-Manipulator Momentum Conservation

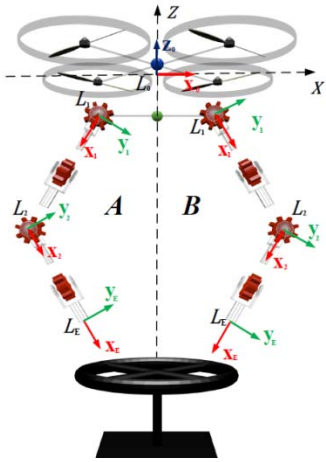


Coupling Momentum and Reaction Null-Space

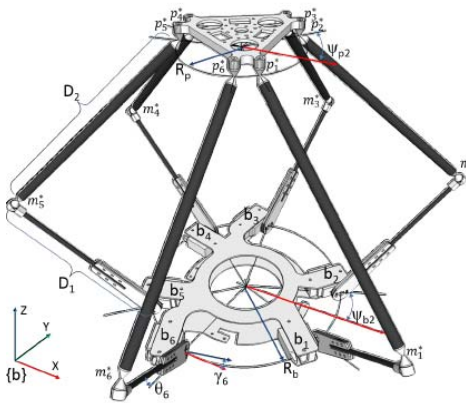
MM-UAV: Mobile-Manipulating UAVs – Sample Demos and Publications



Korpela, C., Orsag, M., Miles, C.D., Oh, P.Y., “Dynamic Stability of an Unmanned Aerial Vehicle,” IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, May 2013



Orsag, M., Korpela, C., **Bogdan, S.**, Oh, P.Y., “Valve turning using a Dual-Arm Aerial Manipulator,” International Conference on Unmanned Aerial Systems (ICUAS), Orlando, FL, May 2014



Danko, T., Oh, P.Y., “Design and Control of a Hyper-Redundant Manipulator for Mobile Manipulating Unmanned Aerial Vehicles,” Journal of Intelligent and Robotics Systems (JINT), Springer-Verlag, Oct 2013

Mobile-Manipulation UAVs: Insertion, Valve-Turning, and Visual-Servoing

Peg-in-hole tasks using a Single-Arm Aerial Manipulator

**Christopher Korpela
Drexel University**



Year 0-1

May 2016 – Nov 2017

Center Mission: To revolutionize **bridge inspection** and preservation methodologies and tools as well as workforce development strategies by developing advanced technologies (e.g. sensors, nondestructive evaluation, **unmanned aerial vehicles**, and **robotics**) and integrating them into practice in order to cost-effectively manage our nation's aging transportation infrastructure.

Approaches (2016 Proposal)

1. UAV uses can of **compressed air** for bridge-cleaning
2. Two UAVs (potentially 1 blimp and 1 rotorcraft) airlift, position, and **operate hoses** from ground

Year 1 Scope of Work (2016 Proposal)

1. Hyper-redundant **serpentine-like limbs** for dexterous manipulation
2. **Multi-UAVs** for coordinated and cooperative missions

Feb 2017 (Project Start)

**MM-UAV needs strong arm
and hand!**

Dr. Paul Oh

From 11/27/17 Progress Report
10-months effort and outcome

PROJECT: Mobile-manipulating UAVs for Sensor Installation, Bridge Inspection and Maintenance

ACCOMPLISHMENTS:

- Theory: impedance-based arm control design ✓
- Design: parallel-based mechanism arm and gripper ✓
- Experiments: pick-and-place and hose-carrying ✓

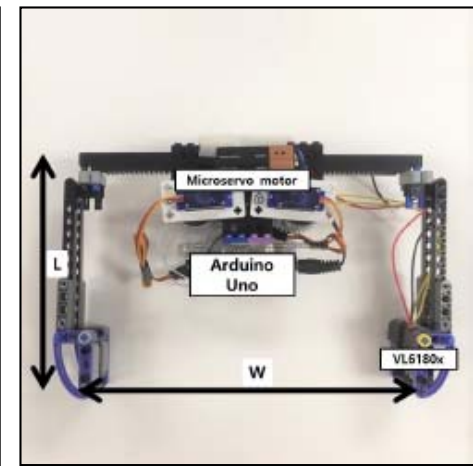
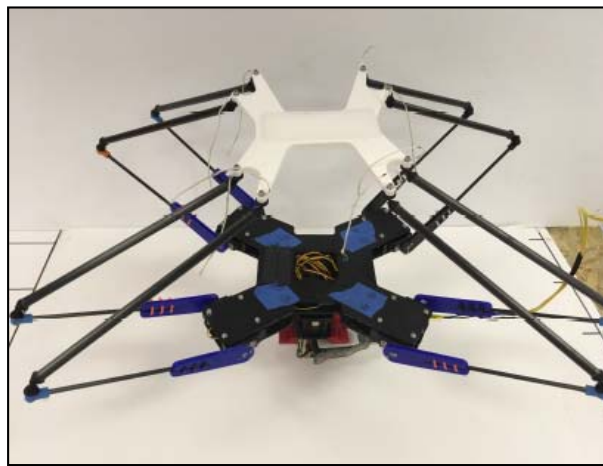
PLANNED ACTIVITIES:

- Design: 4-bar linkage gripper with infrared sensors
- Testing-and-evaluation of gripper and sensor
- Verification-and-validation of gripper and sensor

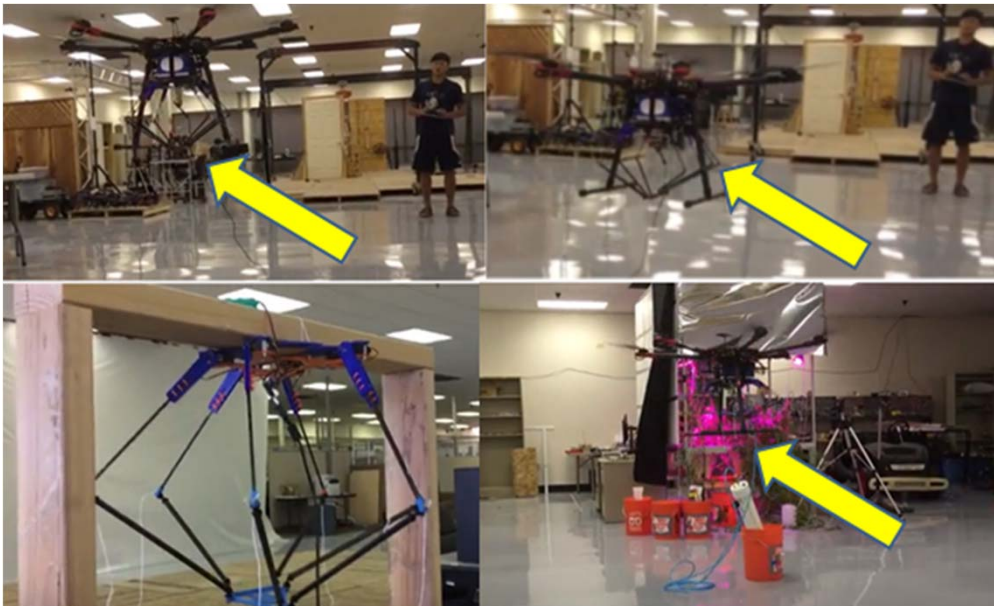
PRODUCTS:

- Hament, B., Oh, P.Y., “Unmanned Aerial and Ground Vehicle (UAV-UGV) System Prototype”, *IEEE International Conference on Consumer Electronics*, Las Vegas, Jan. 2018.

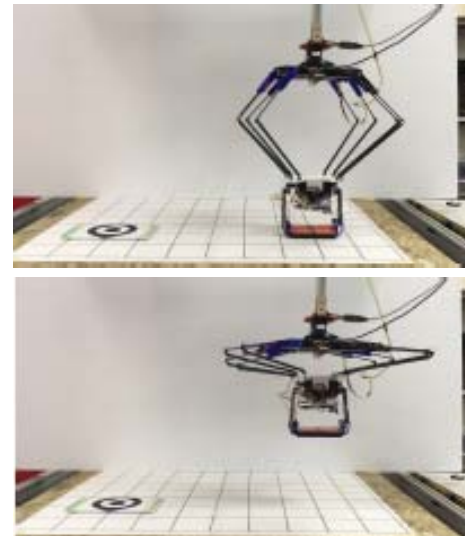




Parallel-based arm (middle) and gripper (right) in stowed position on rotorcraft (left)



Arrows show gripper carrying (water) hose



Gripper pick-and-place test: approaching object (top) and lifting from table (bottom)



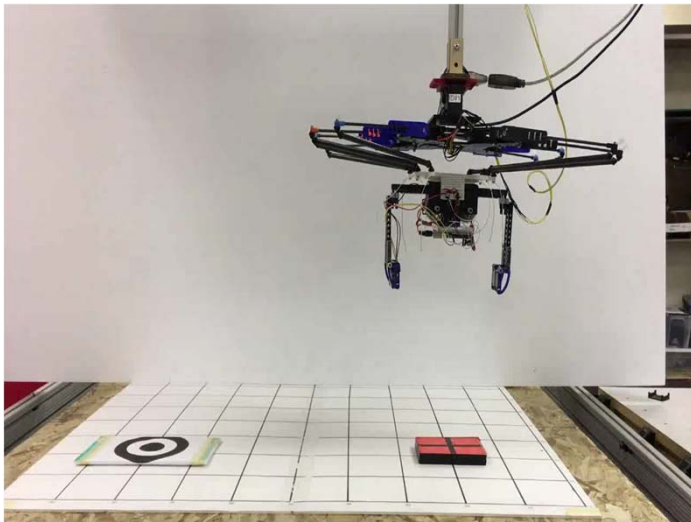
Scope of Work

Effort since Dec 2017 to Present

1. Sensorized 4-bar linkage gripper ✓
2. Test-and-evaluate fluid-handing (air and liquid) ✓

Year 1.5

Dec 2017 – Nov 2018



4-bar Linkage Proof-of-concept (979 gram)

- Test drone (DJI F450) 8.3 Kg payload
- Arm Mass Objective: under 1 Kg




Fire-fighting Drone (Social Media)

<https://www.youtube.com/watch?v=Bm2BVTtir4c>


- **Stable** flight **despite strong jetting**
- Literature domain absent
- Company personnel not from robotics society

Modeling and Analyzing Hose Dynamics



Modeling Hose Dynamics for Unmanned Aerial Vehicles

Blake Hamant and Paul Oh, Drones and Autonomous Systems Lab (DASL)



INTRODUCTION

Bridges and other large pieces of infrastructure accumulate massive amounts of dirt and other particulate that can obscure the structure. Various methods clean structural integrity. Traditionally, these are classified as being removed by humans operating compressed air hoses. A risky and inefficient task. To improve infrastructure cleaning unmanned aerial vehicles (UAV) equipped with hoses could be used to clean the structure in place of human operators.

The challenge in equipping a UAV with a hose is compensating for the reaction forces and torques produced by the hose. In order to counteract these reaction forces and torques, the proposed hoses are carefully modeled and incorporated in the controller architecture.




Fig. 1. Hose mounted in rearward, downward, and center after the UAV. Note how the UAV is not level and hose magnitude is shown in red.




Fig. 2. Hose dynamic will be very different when supporting on the center, rear, and front. See different UAV orientations according to the experimental setup.

Vehicle	Quad	Octo	Array
Mass (kg)	2	10	20
Radius (m)	0	0	10
Arm length (m)	10	10	0

METHODS

- Model force and torque from hoses in Fig. 1, and visualized in Fig. 3.
- Use hose contribution to full UAV dynamic model using characteristics from Fig. 3.
- Use Matlab to find allowable hose angle and other combinations, visualized with Fig. 4.

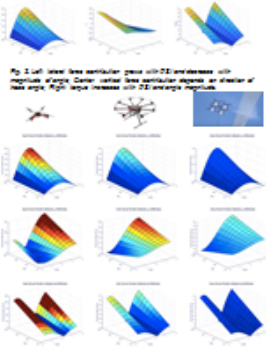


Fig. 3. Left view, rear view, and top view of the UAV. Right view, top view, and rear view of the UAV. Note how the UAV is not level and hose magnitude is shown in red.

Fig. 4. Results represent simulated responses for respective UAV. Values represent the size of each operating mode. 0 is either greater than or equal to 100% thrust.

RESULTS

Initial results explore stability with permutations of flow from 20 to 200 PSI and hose angles between 0 to 90 degrees. The general force components and torque from the hose are visualized in Fig. 3.

The general force and torque from Fig. 3 are applied to vehicle-specific Matlab simulators representing three common types of UAV shown in Fig. 1: quadcopter, octocopter, and multi-robot array. For each vehicle, the power thrusters required to maintain 0 translational and angular accelerations are calculated. The outputs in Fig. 4 represent the robot's required power in the ground plane for various combinations of PSI and hose angles. For each combination, some percent thrust is required to hold the vehicle stable during hose operation between 60% and less than 100% thrust is considered a "warning" zone (shaded yellow) and orange shading 100% thrust or greater is shaded red. Safe take-off and configuration are shaded blue, with darker blues corresponding to a lower percent thrust required for stability.

CONCLUSIONS

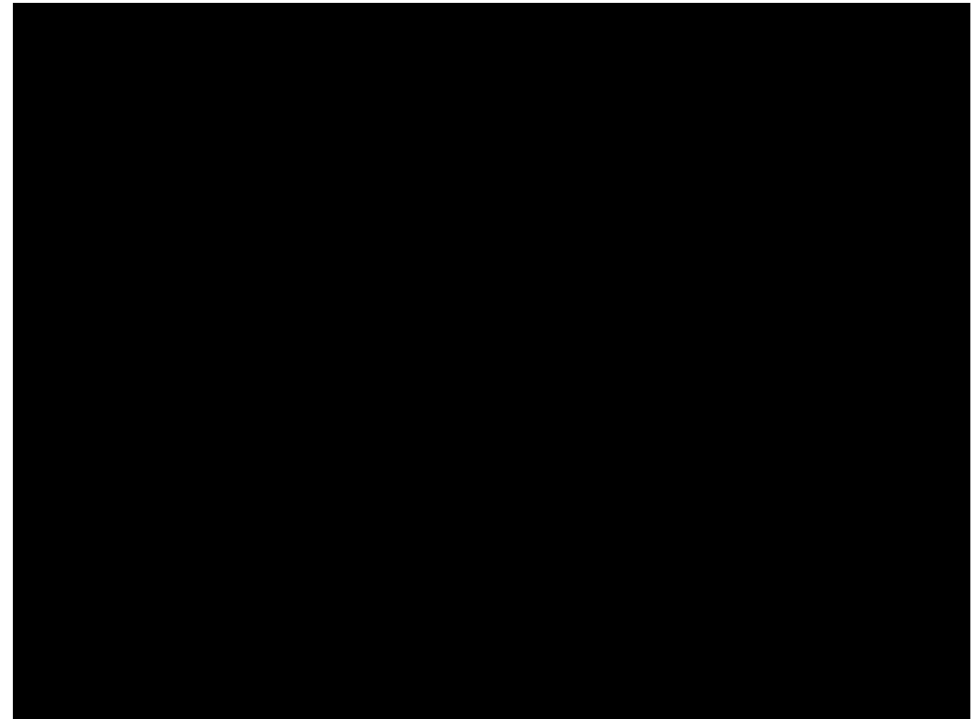
The modeling presented suggests vehicle-specific limits on hose PSI and angle to maintain zero instability. Hose dynamics are largely negligible for vehicles with momenta and thrust. However, even slight low-power UAV can easily use surprisingly high PSI with careful hose angle selection. Results also strongly indicate on critical mounting orientation. Good design means careful angle bandwidth for safe take-off. Files for Spring for Linux, ROS, and other platforms are available for the two topics.

REFERENCE

B. Mahony, V. Kumar, and P. Coria, "Robotics for Unmanned Aerial Vehicles: Modeling, Estimation, and Control of a Quadrotor," *IEEE Robotics and Automation Magazine*, vol. 19, Sept. 2012, pp. 20-32.

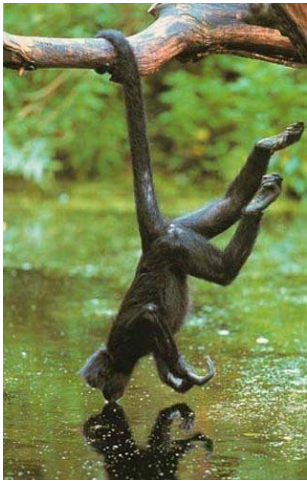
ACKNOWLEDGEMENTS

Thank you to the US Department of Transportation for funding and to the INSPIRE research center for supporting and organizing the interdisciplinary collaboration.

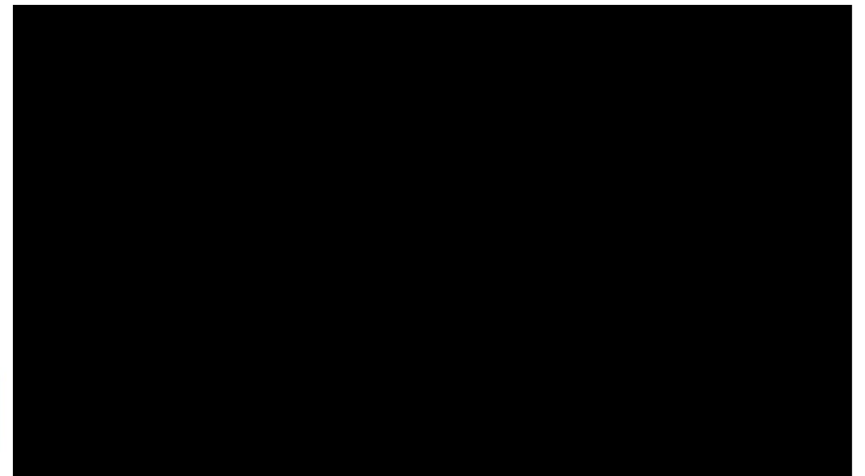
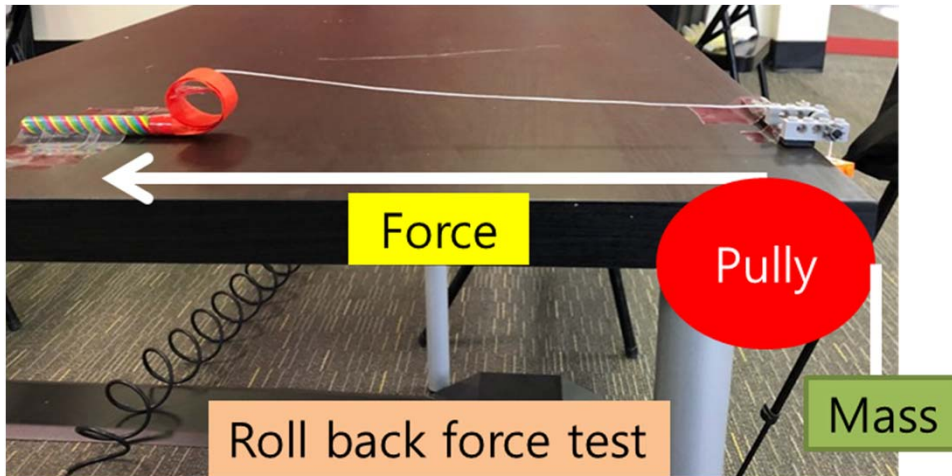


- Tests: 50 to 200 PSI compressed air
- Tests: Quad, Octo, and Array UAV
- Large Moment of Inertia = stability
- Large Thrust = stability
- **Hose mounting location = stability**

Hyper-redundant Serpentine Manipulators



Bridge-maintenance: perching * ballistic actions * nailing * debris-collection





Bio-inspired "soft" manipulator: party whistle

Summary

UAV Continuum of Research

- Control and Navigation Needs: well-understood
- Field-of-view: tools (e.g. chase view) available but perhaps not needed
- Aerial Manipulation needs: potential (and limitations) generally understood

INSPIRE: Aerial Manipulation for Bridge Applications

- 2016 Proposal: Parallel Mechanism Arm 
- 2017 Activity: Arm design; 4-bar linkage hand; underlying control theory 
- 2018 Activity: Air jet handling; Hyper-redundant bio-inspired manipulator

Discovery-led Research Direction (Potential Future Work)

- Optimal hose mount design (based on location, thrust and moment of inertia)
- Epoxy applicator using bio-inspired “frog tongue”

Acknowledgements

INSPIRE Transportation Center thru UDDOT/OST-R grant #69A3551747126

Special Thanks: Prof. Genda Chen and Amy Gillman!