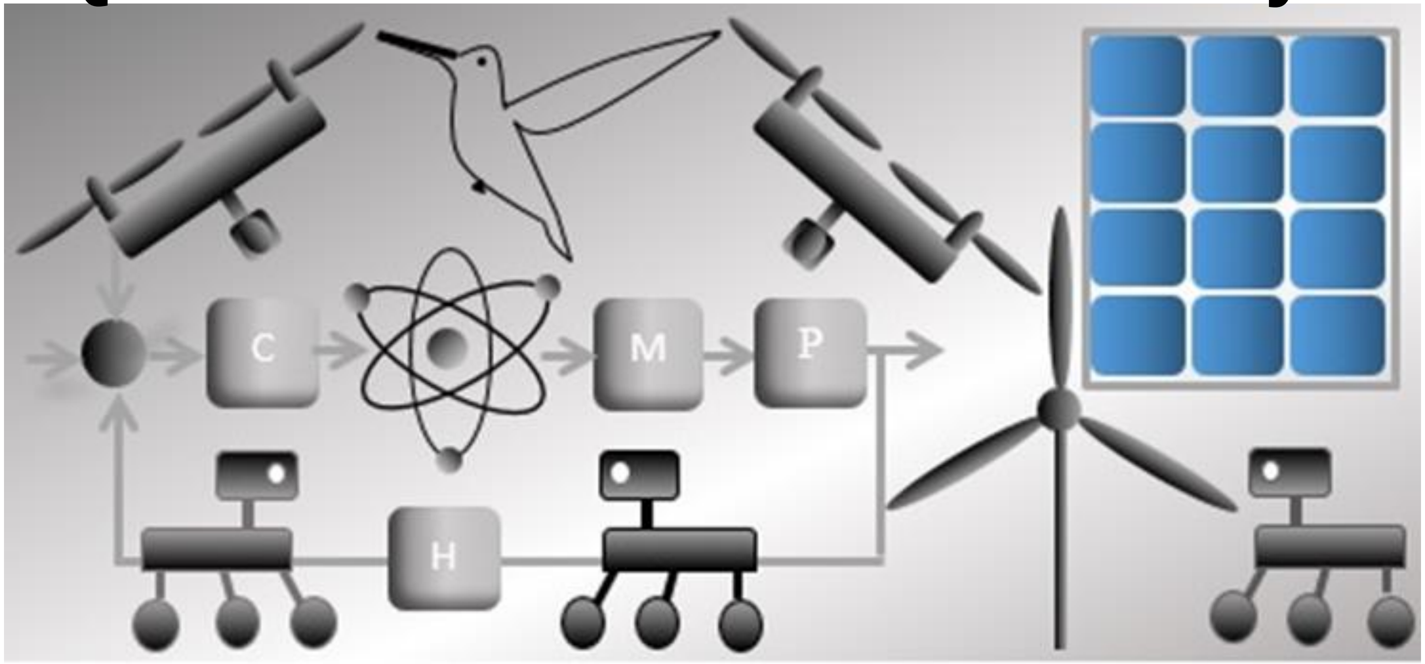
Self-powered Dynamic Systems
Bio-inspired Dynamic Systems
Quantum Robotics and Autonomy



Farbod Khoshnoud, PhD

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Department of Aerospace Engineering, Caltech

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https://www.cpp.edu/faculty/fkhoshnoud/index.shtml

Outline

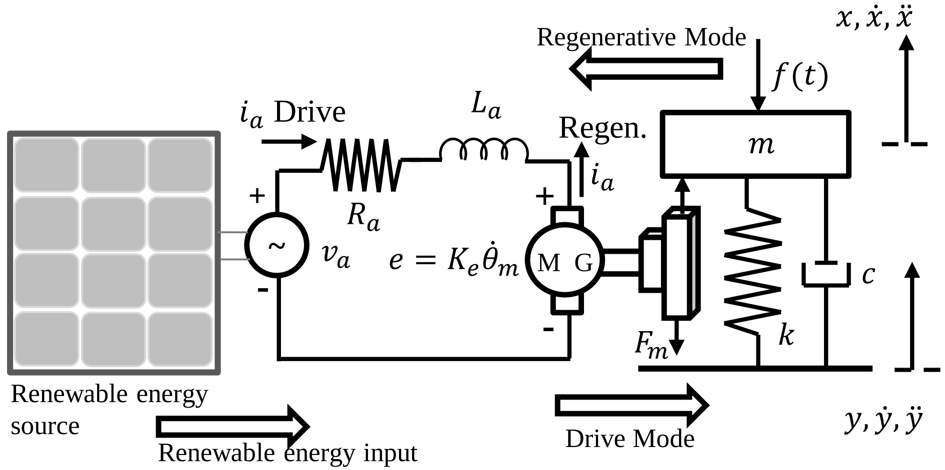
- Self-powered Dynamic Systems
- Nature/Bio-inspired Dynamic Systems
- Quantum Multibody Dynamics, Robotics, and Autonomy
- Optimal Uncertainty Quantification for engineering Systems

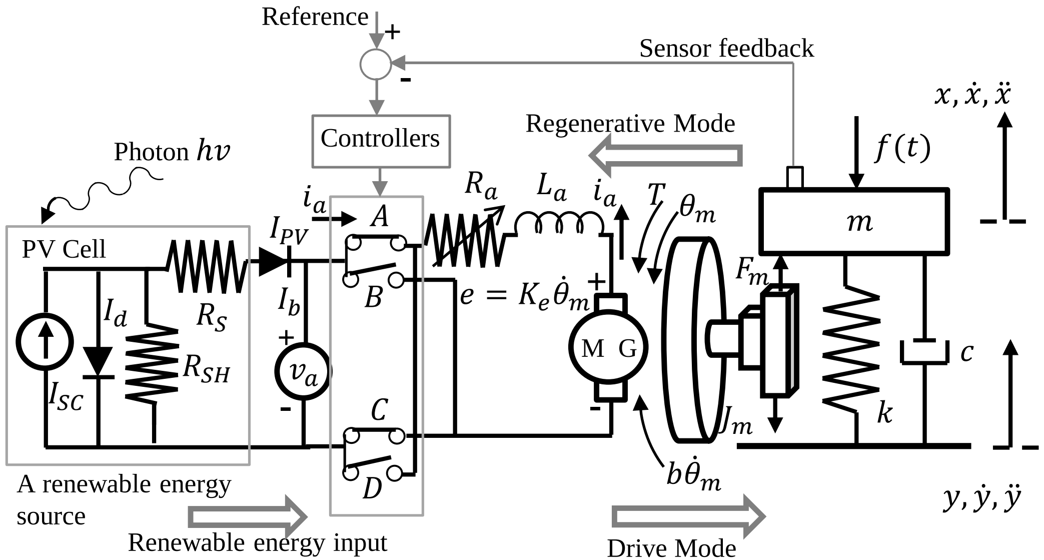
- Self-powered Dynamic Systems
- Nature/Bio-inspired Dynamic Systems
- Quantum Multibody Dynamics, Robotics, and Autonomy
- Optimal Uncertainty Quantification for engineering Systems

Self-powered Dynamic Systems

https://en.wikipedia.org/wiki/Self-powered_dynamic_systems

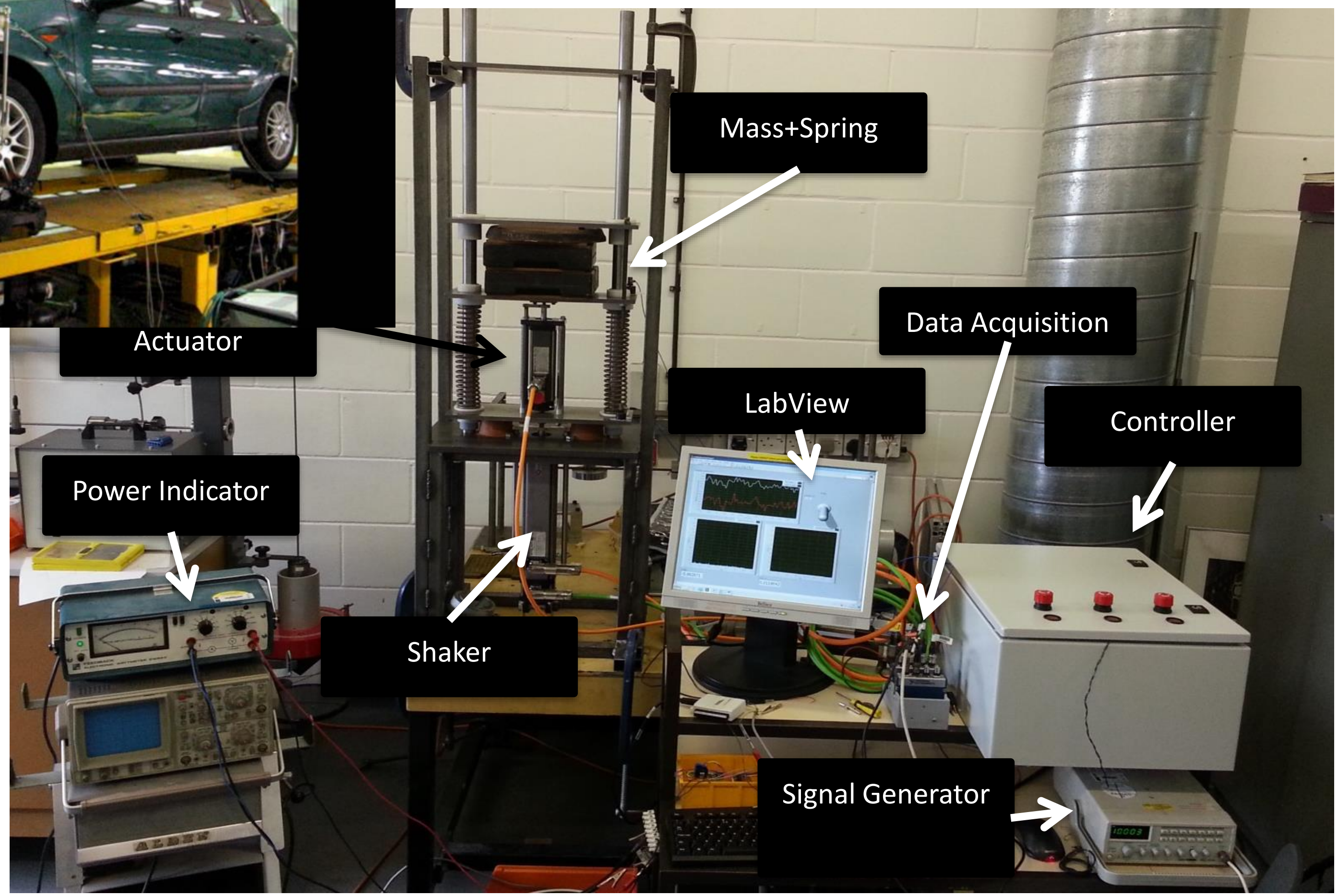
Energy Independent (self-sustained) Sensors and Actuators/Systems





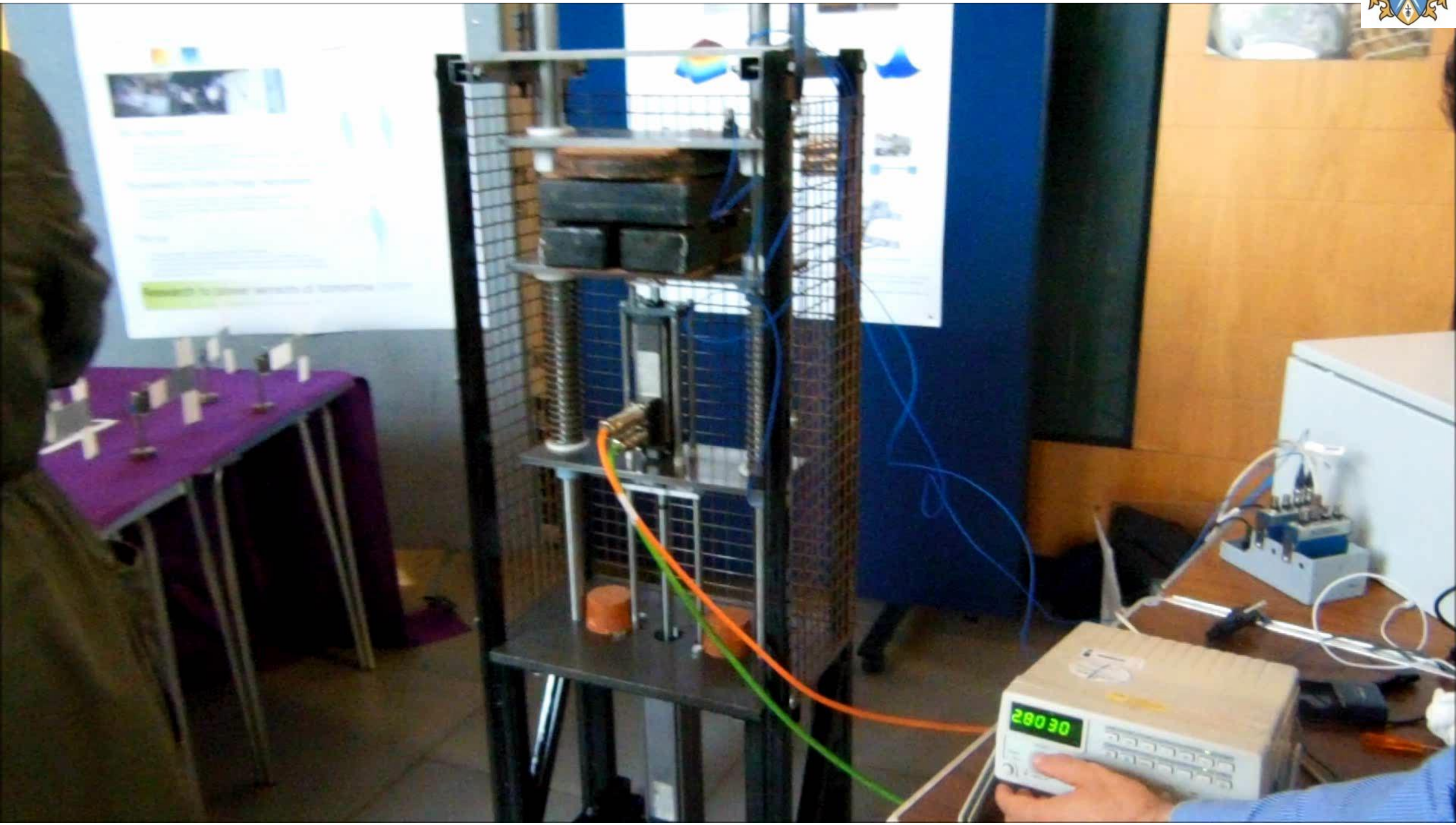
Farbod Khoshnoud, M. M. McKerns, Clarence W. De Silva, Ibrahim Esat, Houman Owhadi, **Self-powered Dynamic Systems in the framework of Optimal Uncertainty Quantification**, ASME Journal of Dynamic Systems, Measurement, and Control, Volume 139, Issue 9, 2017.

Self-powered Control



Farbod Khoshnoud, Dario Robinson (Pomona Police), Ibrahim I. Esat (Brunel), Clarence W. De Silva (UBC), Marco B. Quadrelli (JPL), **Research-informed service-learning in Mechatronics and Dynamic Systems**, *American Society for Engineering Education conference*, Los Angeles, April 4-5, 2019, [Paper ID #27850](#).

The experimental energy harvesting rig



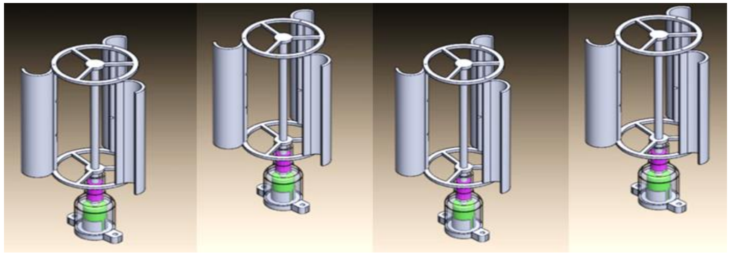
Farbod Khoshnoud, Y. Zhang, R. Shimura, A. Shahba, G. Jin, G. Pissanidis, Y.K. Chen, Clarence W. De Silva, **Energy regeneration from suspension dynamic modes and self-powered actuation**, *IEEE/ASME transaction on Mechatronics*, Volume: 20, Issue: 5, pp. 2513 - 2524, 2015.

Video Link

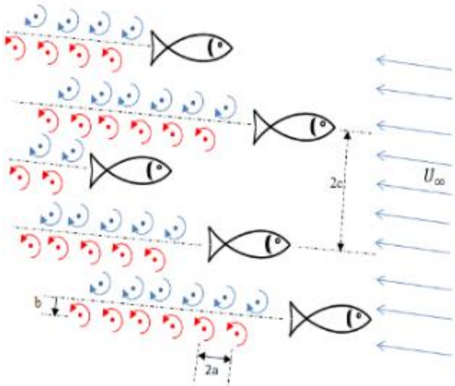
Farbod Khoshnoud, Dinesh B. Sundar, Nuri M. Badi, Yong K. Chen, Rajnish K. Calay and Clarence W. de Silva, **Energy harvesting from suspension system using regenerative force actuators**, International Journal of Vehicle Noise and Vibration *Vol. 9, Nos. 3/4, pp. 294 - 311, 2013.*

Mechatronics Systems engineering

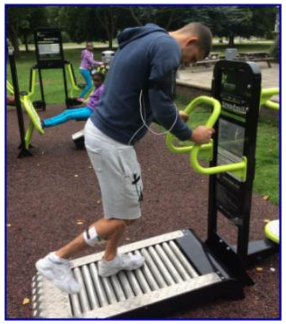
Solar aircraft



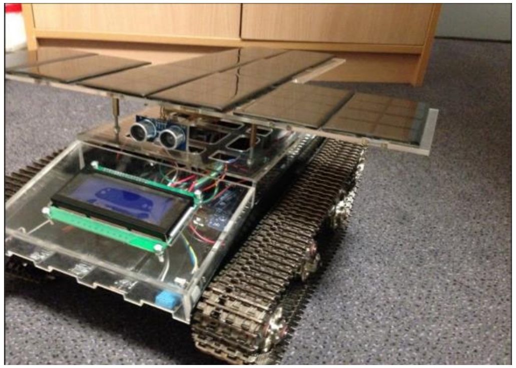
Bio-inspired vertical axis wind turbines



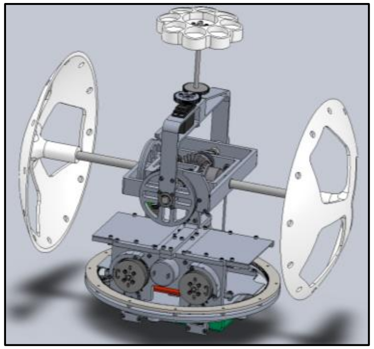
Energy from human motion



Energy harvesting from human motion

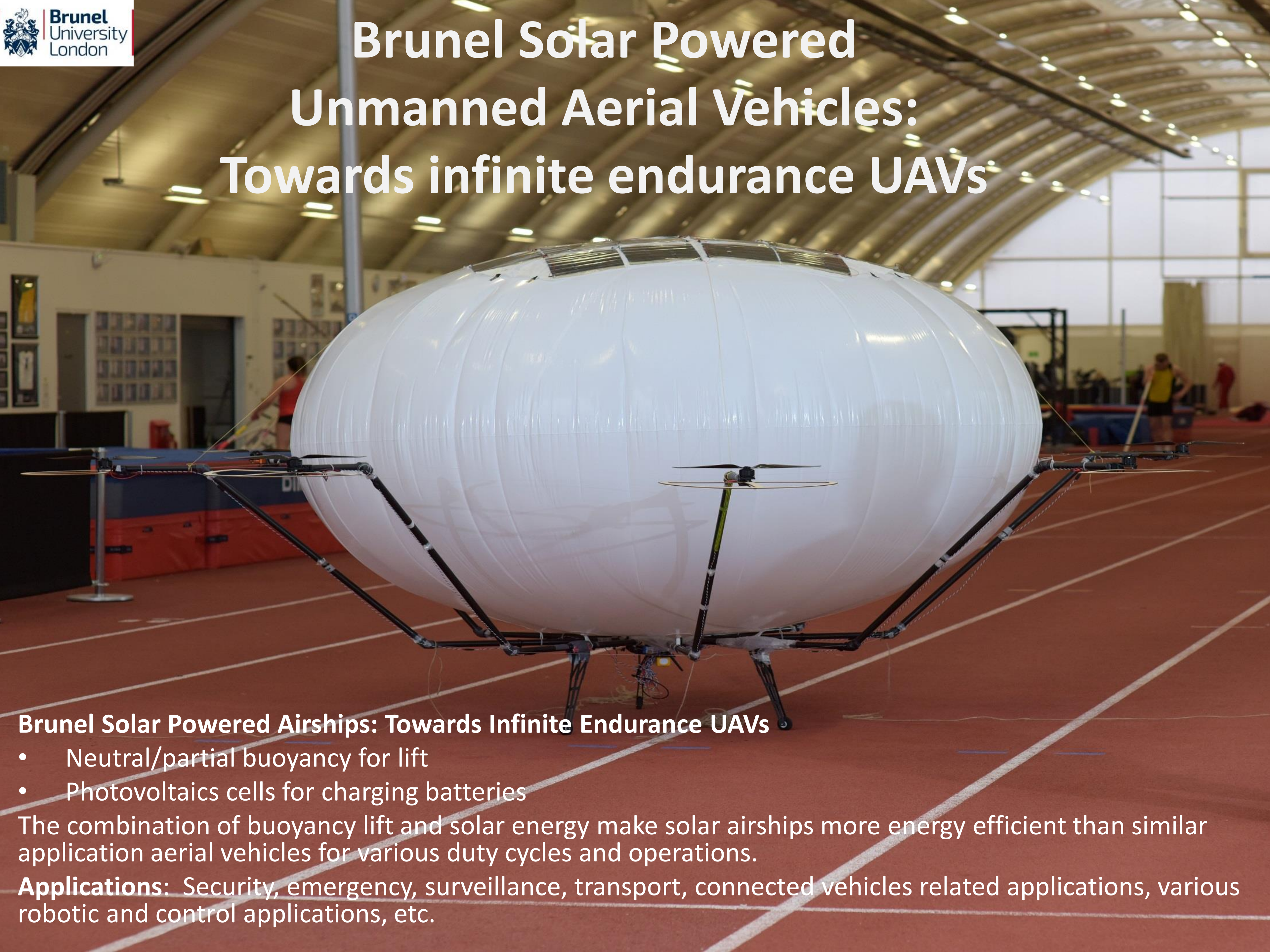


Autonomous vehicles



BB-8 Droid
Mechatronics Club

Brunel Solar Powered Unmanned Aerial Vehicles: Towards infinite endurance UAVs



Brunel Solar Powered Airships: Towards Infinite Endurance UAVs

- Neutral/partial buoyancy for lift
- Photovoltaics cells for charging batteries

The combination of buoyancy lift and solar energy make solar airships more energy efficient than similar application aerial vehicles for various duty cycles and operations.

Applications: Security, emergency, surveillance, transport, connected vehicles related applications, various robotic and control applications, etc.

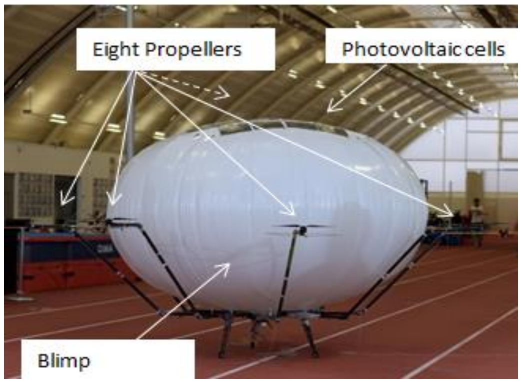
Self-Powered Solar Autonomous Aerial Vehicles

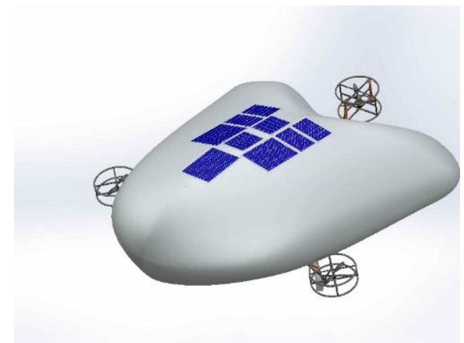
Project Summary

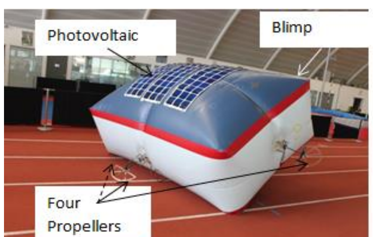
Building a self-sustained solar powered aerial vehicle towards "infinite" endurance operation as a self-powered system.

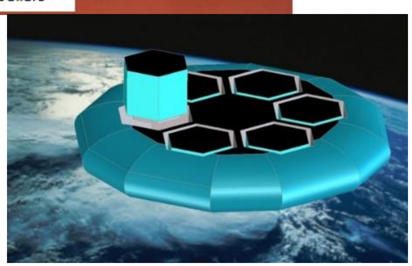
Benefits and applications: no limit

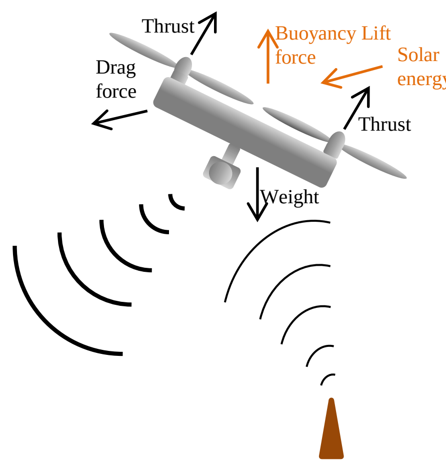
Emergency Response, Delivery, Traffic control, Agricultural, Surveillance, Search and rescue, Security, Telehealth, Beaming internet, Aerial robotics, Maintenance…

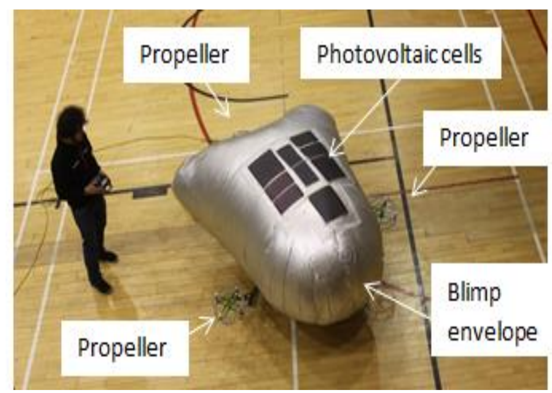












Farbod Khoshnoud, Ibrahim I. Esat (Brunel), Clarence W. De Silva (UBC), Jason Rhodes, Alina Kiessling (JPL), Marco B. Quadrelli (JPL), **Self-powered Solar Aerial Vehicles: towards infinite endurance UAVs**, *Unmanned Systems*, Vol. 8, No. 2, 2020, pp. 1–23. [Preprint PDF]

Drone commercial use case: internet/media beaming

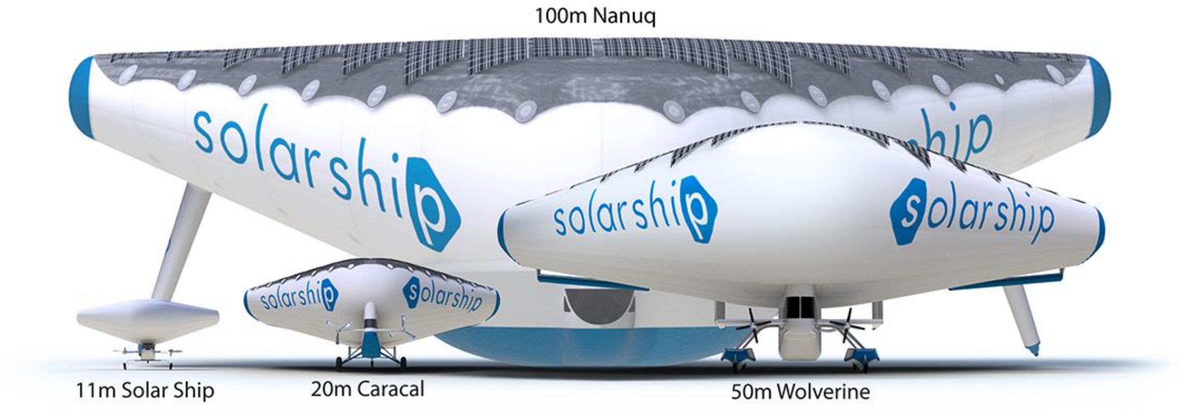
IDTechEx report on [‘Electric UAV Drones: Autonomous Energy Independent 2017-2027’]

State-of-the-Art


Lockheed Martin Hybrid Airship

Airlander 10


Aerostat



NASA Jet Propulsion Laboratory
20-20-20 Airship Challenge

Applications:

Astronomy: **using telescopes on the airship to create high-resolution images of stars and other objects.**

Earth Science: **data collected by airships for investigating climate change and weather.**

"Follow weather patterns, even get above a hurricane. A satellite can't do that because its orbit can't be changed," Jason Rhodes.

Telecommunication: **providing wireless Internet to remote areas.**

Source: NASA JPL:
http://www.jpl.nasa.gov/news/news.php?feature=4391

Farbod Khoshnoud, I. I. Esat, C. W. de Silva, Jason D. Rhodes, Alina Kiessling, Marco B. Quadrelli, **Solar Powered Autonomous Aerial Vehicles: Towards infinite endurance UAVs**, *Unmanned Systems Journal*, 2019

Drones: from energy harvesting to energy independence

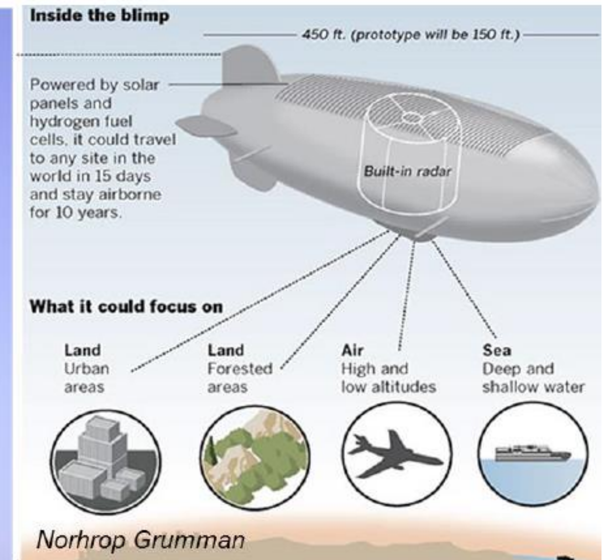
Dirisolar


Lockheed Martin


Turtle airship


Brunel Solar Powered Robotic Airship 2016


China Aerospace



Norhrop Grumman

- Energy independence is the endgame of electric vehicles?

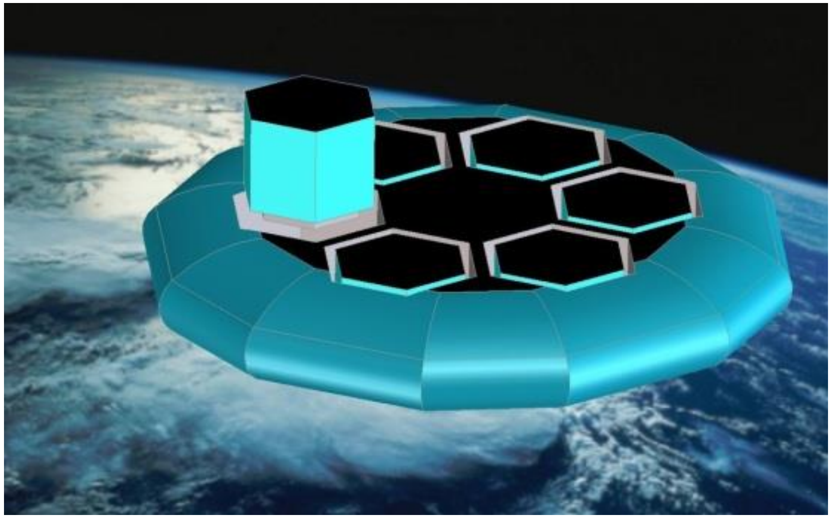
IDTechEx report on ‘Energy Independent Electric Vehicles Land, Water, Air 2017: 2037’

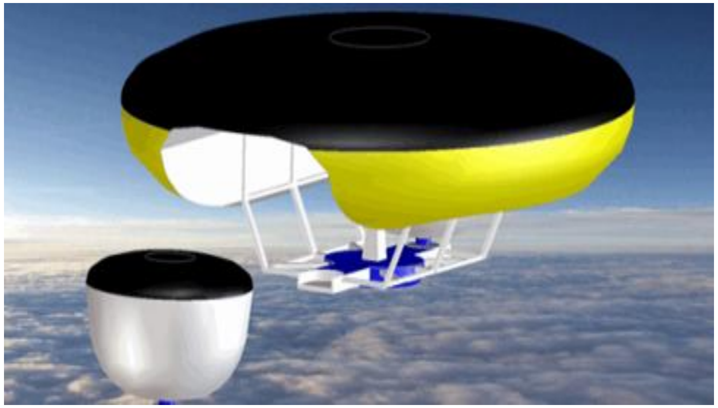
Solar Powered UAVs (3 million euros)

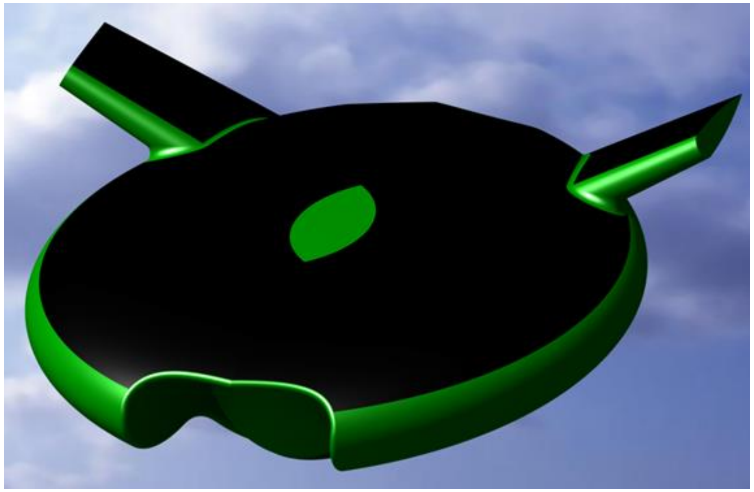
SEVENTH FRAMEWORK PROGRAMME

Multibody Advanced Airship for Transport (MAAT)

Diameter:	350m
Height:	70m
Cruising altitude:	15,600m
Max Speed:	300km/h
Power generating capacity: 3-4MW	
Capacity:	510 passengers
Weight:	500 tons
Selling cost:	$400m
Annual operating cost:	$24m

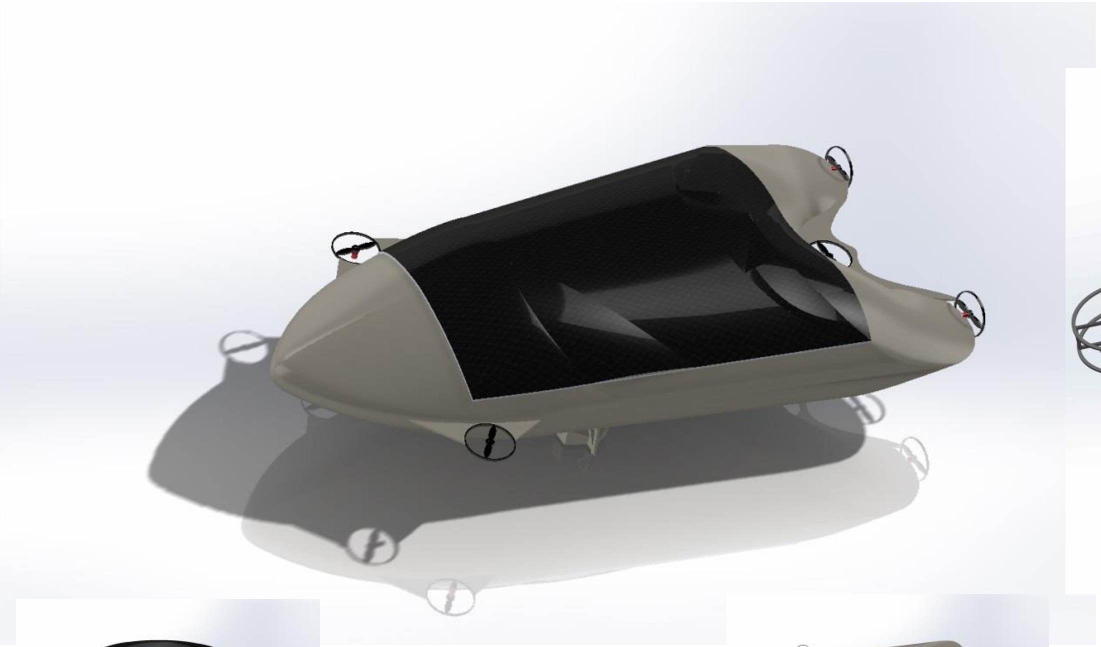


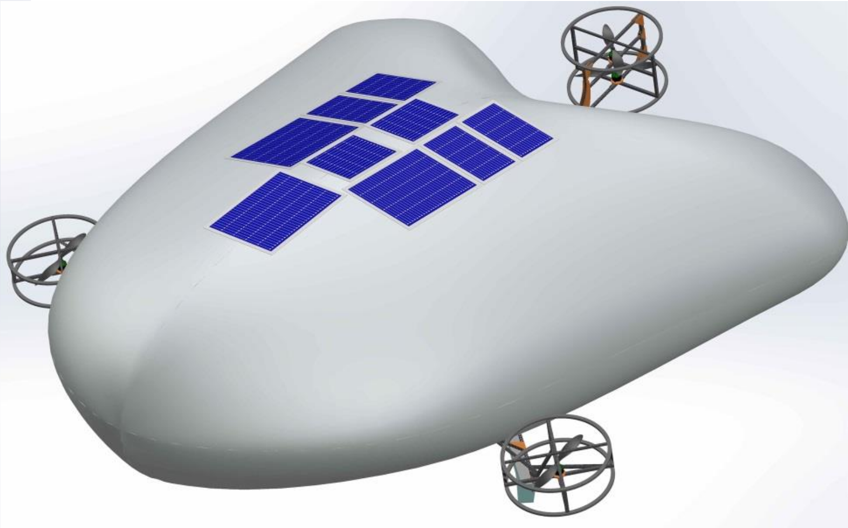


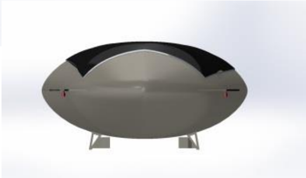


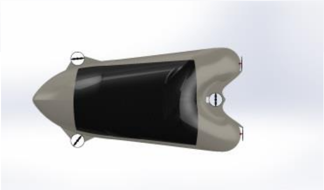
Reference:
Farbod Khoshnoud, Y.K. Chen, and R.K. Calay, **On Power and Control Systems of Multibody Advanced Airship for Transport,** *International journal of Modelling, Identification and Control, Int. J. Modelling, Identification and Control, Vol. 18, No. 4, 2013.*

Various Designs for Unmanned Aerial Vehicles (UAVs)



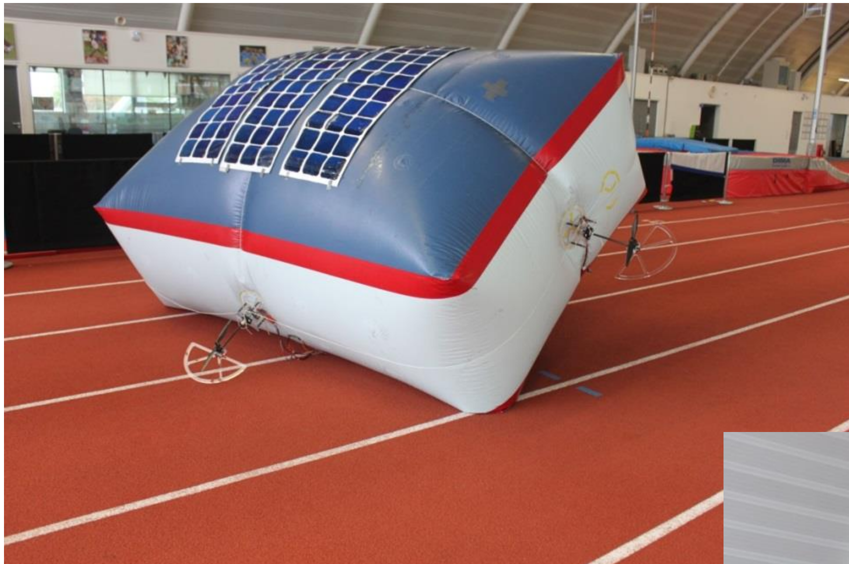


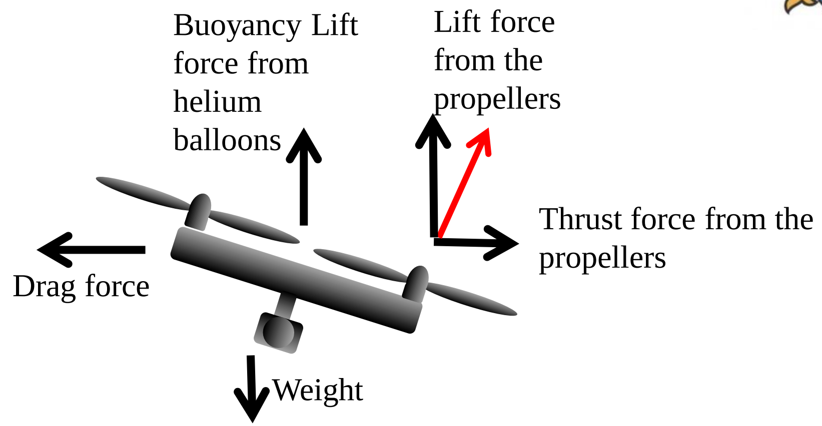




Students: Oliver Salsbury, Daniel Raineri, Giuliano Morreale, Timothy Taylor, Daniel Sutch, Psam Elyon, George Glass, Nejc Terbuc, Daniel Phillips, Dogan Guler, Conrad Warden, Kwan Wong, Mohamed Farah, Daniel Cheung, Nur Muhar, Latifah Mohd Bakri, Nik Mohamad Shafie, Syafiyyah Naamat, Ahmad Mohd Fauzee, Muhammad Nawawi

Quadrotor solar powered UAVs





Brunel Solar-powered airship: Towards infinite endurance UAVs

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The combination of buoyancy lift and solar energy make solar airships more energy efficient than similar application aerial vehicles for various duty cycles and operations.

Applications: Security, emergency, surveillance, transport, connected vehicles related applications, various robotic and control applications, etc.

Technology Readiness Level

£25million airship Airlander 10 (Source: Daily Mail, August 25, 2016).

Much of the world has no access to paved roads. Vast cargo-bearing airships could reach places that planes and trucks can't.

Octorotor solar powered UVs

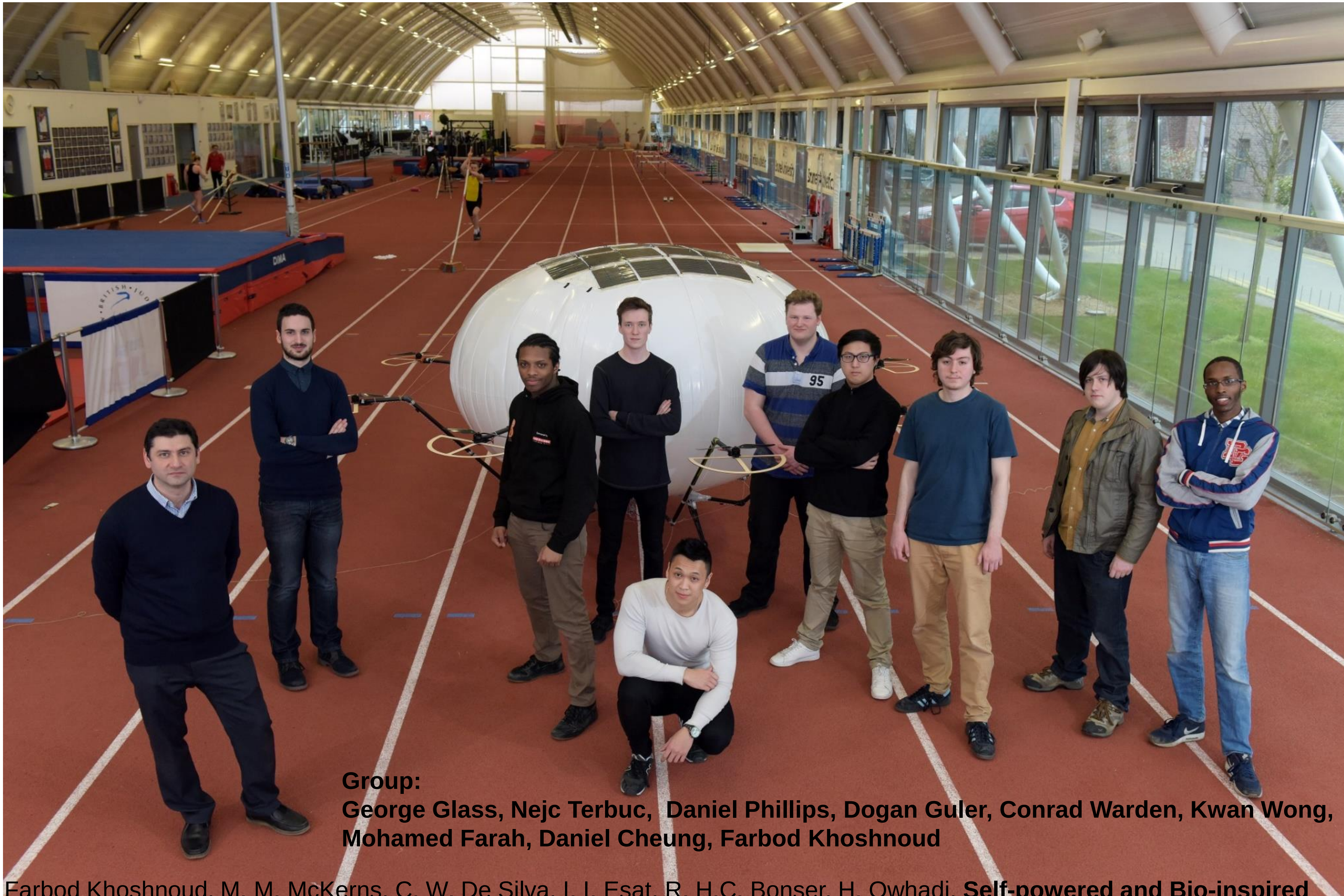
https://www.youtube.com/watch?v=u9fBr7l-Lrw

Students: George Glass, Nejc Terbuc, Daniel Phillips, Dogan Guler, Conrad Warden, Kwan Wong, Mohamed Farah, Daniel Cheung

Video Link

Farbod Khoshnoud, Ibrahim I. Esat (Brunel), Clarence W. De Silva (UBC), Jason Rhodes, Alina Kiessling (JPL), Marco B. Quadrelli (JPL), **Self-powered Solar Aerial Vehicles: towards infinite endurance UAVs**, *Unmanned Systems*, Vol. 8, No. 2, 2020, pp. 1–23. [Preprint PDF]

Octorotor solar powered UAVs - Octoship



Group:
George Glass, Nejc Terbuc, Daniel Phillips, Dogan Guler, Conrad Warden, Kwan Wong, Mohamed Farah, Daniel Cheung, Farbod Khoshnoud

Farbod Khoshnoud, M. M. McKerns, C. W. De Silva, I. I. Esat, R. H.C. Bonser, H. Owhadi, **Self-powered and Bio-inspired Dynamic Systems: Research and Education**, ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, Arizona, USA, 2016.

Brunel UAVs

Bocsh Award for "the Best project in mechanical engineering" from the Bocsh Ltd company, 2016.
From left: Farbod Khoshnoud, Mark Woodcock from Bosch Ltd, Nejc Terbuc, Daniel Phillips, Vice-Chancellor and President Professor Julia Buckingham, Conrad Warden, Kwan Wong, George Glass, Daniel Cheung; Sitting: Dogan Guler, Mohamed Farah

Trirotor Solar-Fuel Cell Powered Vehicles: Towards Infinite endurance UVs

Students: Oliver Salsbury, Daniel Raineri, Giuliano Morreale, Timothy Taylor, Daniel Sutch, Psam Elyon

Farbod Khoshnoud, Ibrahim I. Esat (Brunel), Clarence W. De Silva (UBC), Jason Rhodes, Alina Kiessling (JPL), Marco B. Quadrelli (JPL), **Self-powered Solar Aerial Vehicles: towards infinite endurance UAVs**, *Unmanned Systems*, Vol. 8, No. 2, 2020, pp. 1–23. [Preprint PDF]

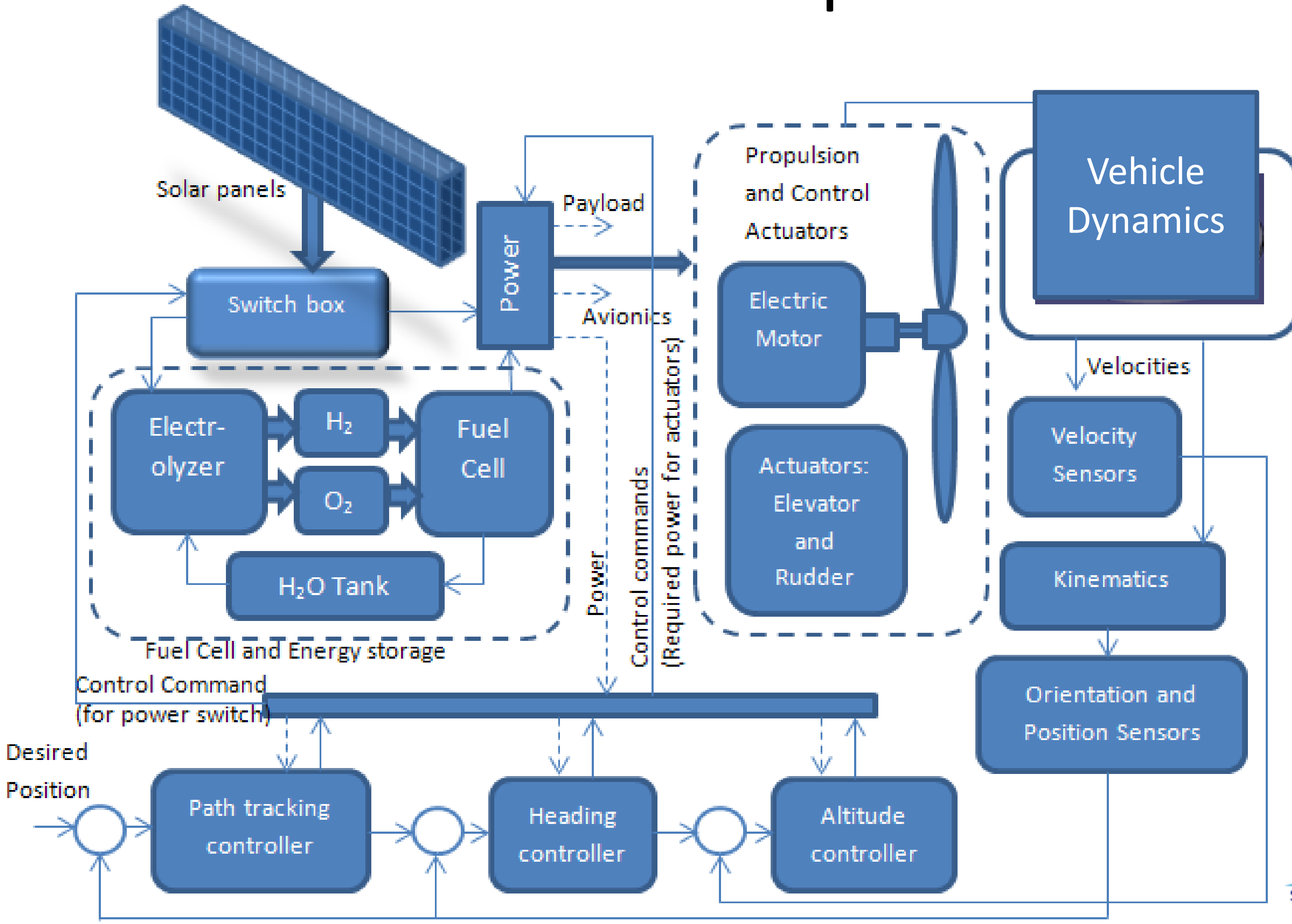
Trirotor solar-fuel cell UAVs

Students: Oliver Salsbury, Daniel Raineri, Giuliano Morreale, Timothy Taylor, Daniel Sutch, Psam Elyon

Brunel UAVs

Airbus Prize for "Excellence and innovation in design and engineering relating to the aviation and aerospace industries" received from the Airbus UK president Paul Kahn, 2016, Brunel University London, UK.
From left: Farbod Khoshnoud, Daniel Sutch, Oliver Salsbury, Psam Elyon, Vice-Chancellor and President Professor Julia Buckingham, Airbus president Paul Kahn, Giuliano Morreale, Timothy Taylor, Daniel Raineri

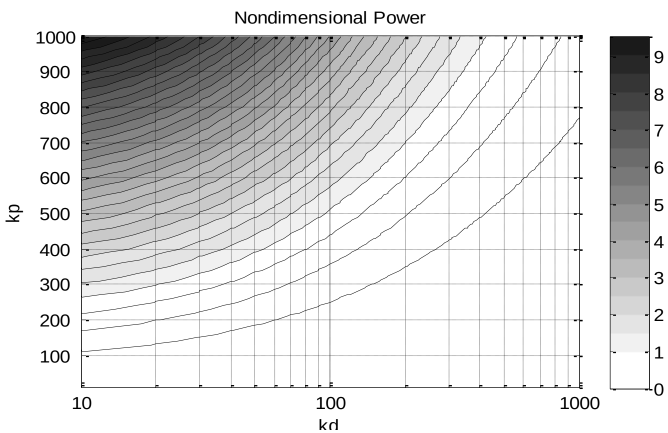
Autonomous solar-fuel cell powered vehicles

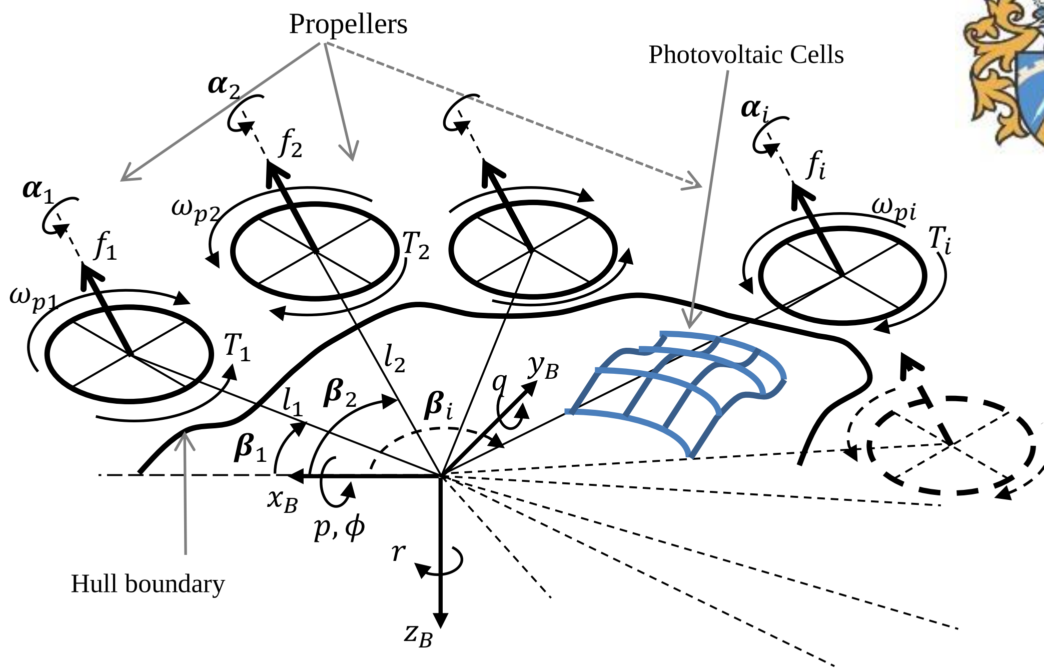


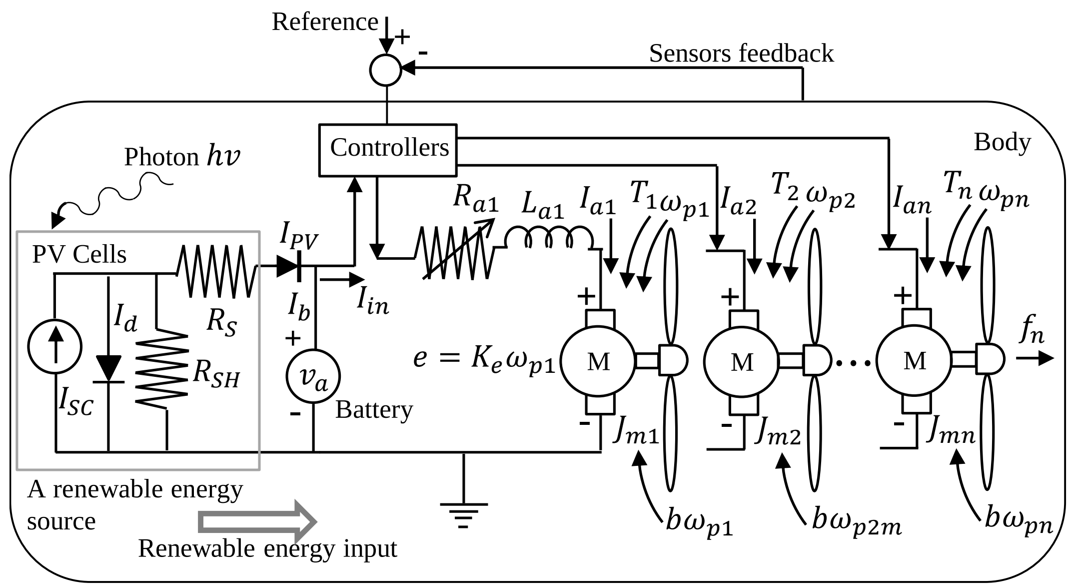
Farbod Khoshnoud, Clarence W. De Silva, et al., **Mechatronics: Fundamentals and Applications**, Taylor & Francis / CRC Press, 2015.

Self-powered Vehicles:

Towards Infinite Endurance UVs







F. Khoshnoud, I. I. Esat, C. W. de Silva, Jason D. Rhodes, Alina Kiessling, Marco B. Quadrelli, **Solar Powered Autonomous Aerial Vehicles: Towards infinite endurance UAVs**, *Unmanned Systems Journal*, 2019

Research-led Service-Learning

Autonomous traffic monitoring, and situation awareness

Ref: Farbod Khoshnoud, Dario Robinson, C. W. de Silva, I. I. Esat, R.H.C. Bonser, M. B. Quadrelli, **Research-informed service-learning in Mechatronics and Dynamic Systems**, ASEE PSW 2019 Conference, April 4-6, 2019, Los Angeles, CA.

- Self-powered Dynamic Systems
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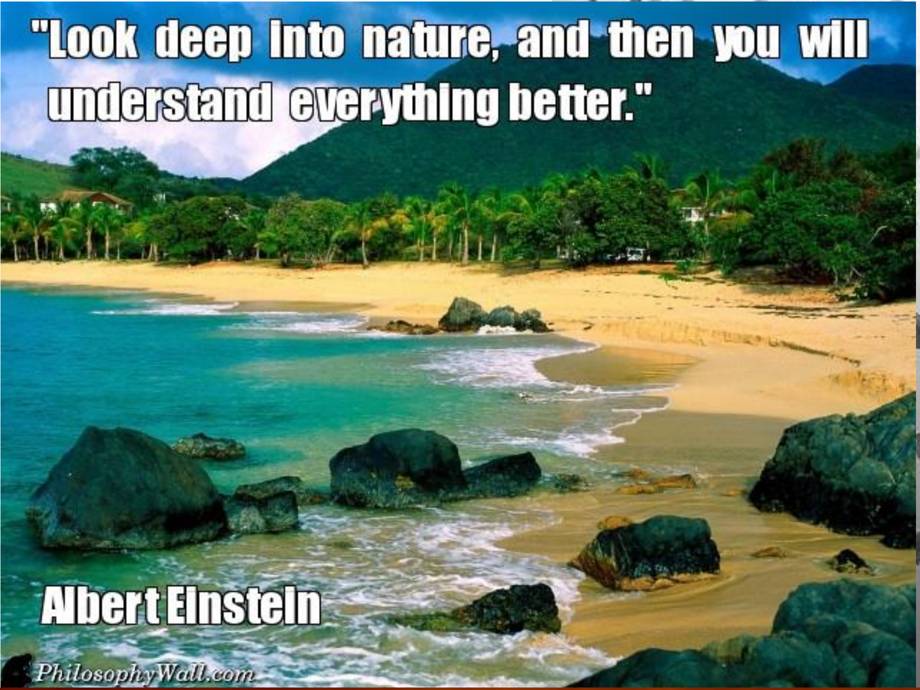
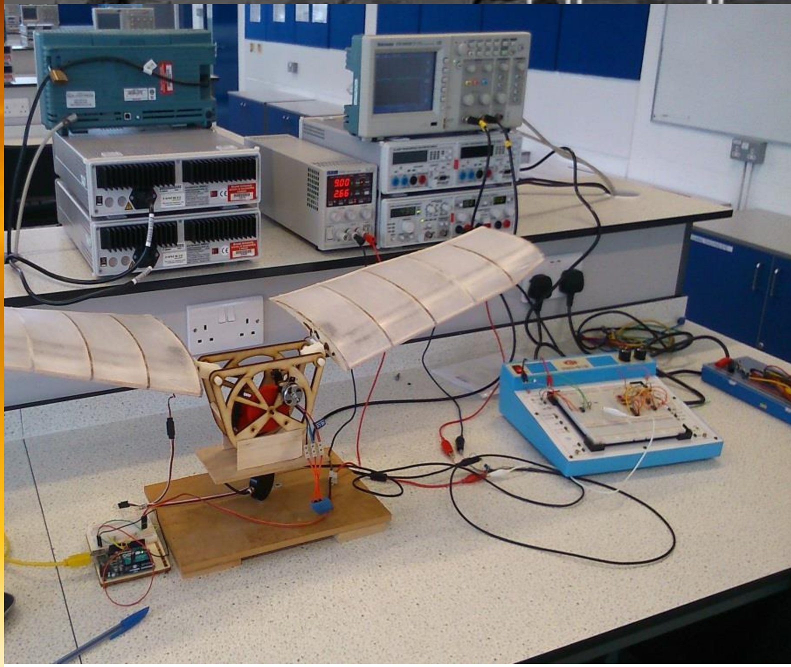
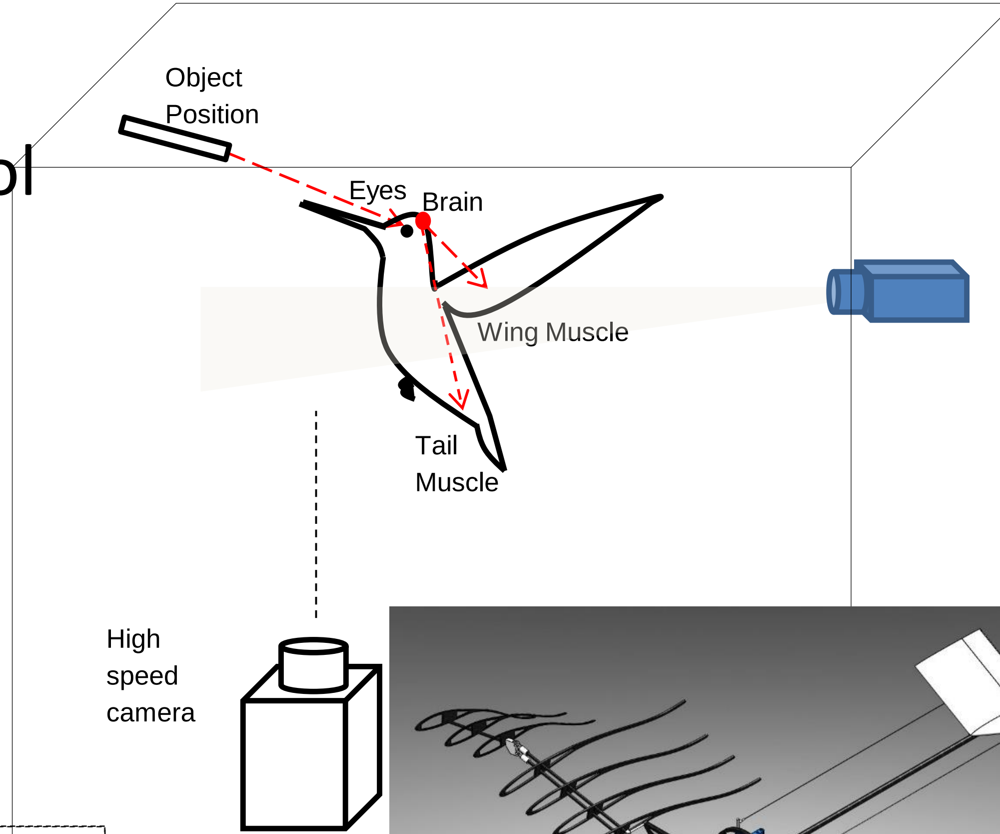
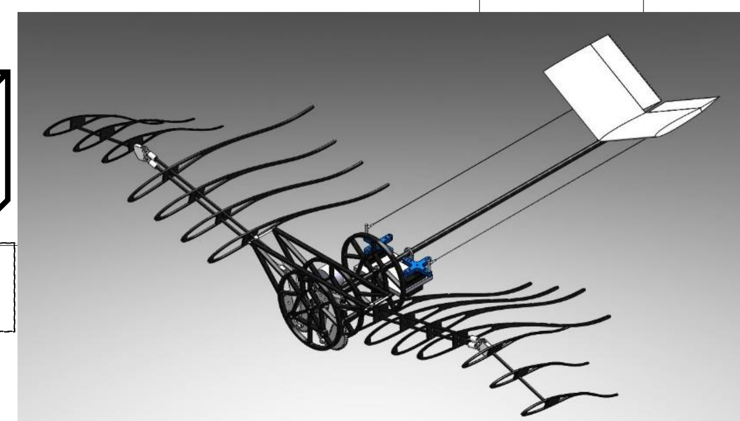
- Optimal Uncertainty Quantification for engineering Systems

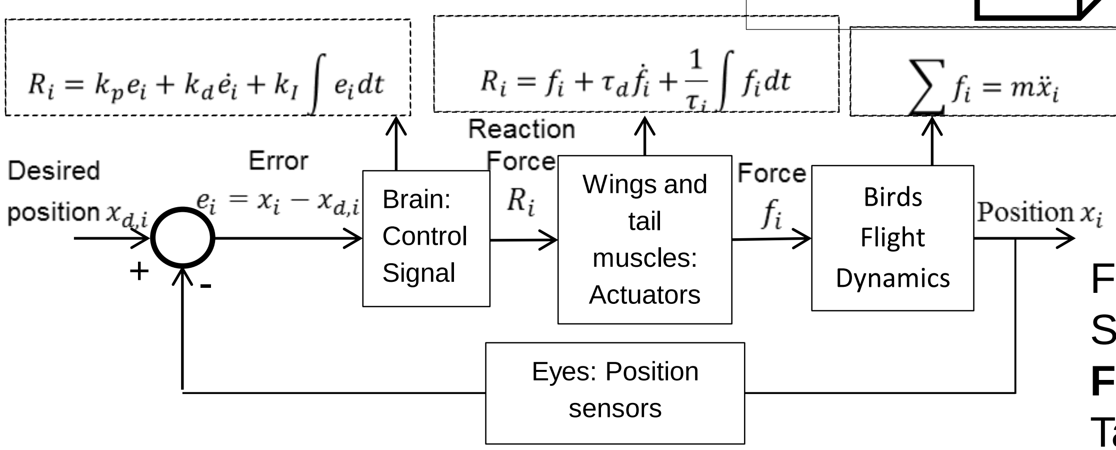

"Look deep into nature, and then you will understand everything better."
Albert Einstein
PhilosophyWall.com

Bio-inspired Flight Control



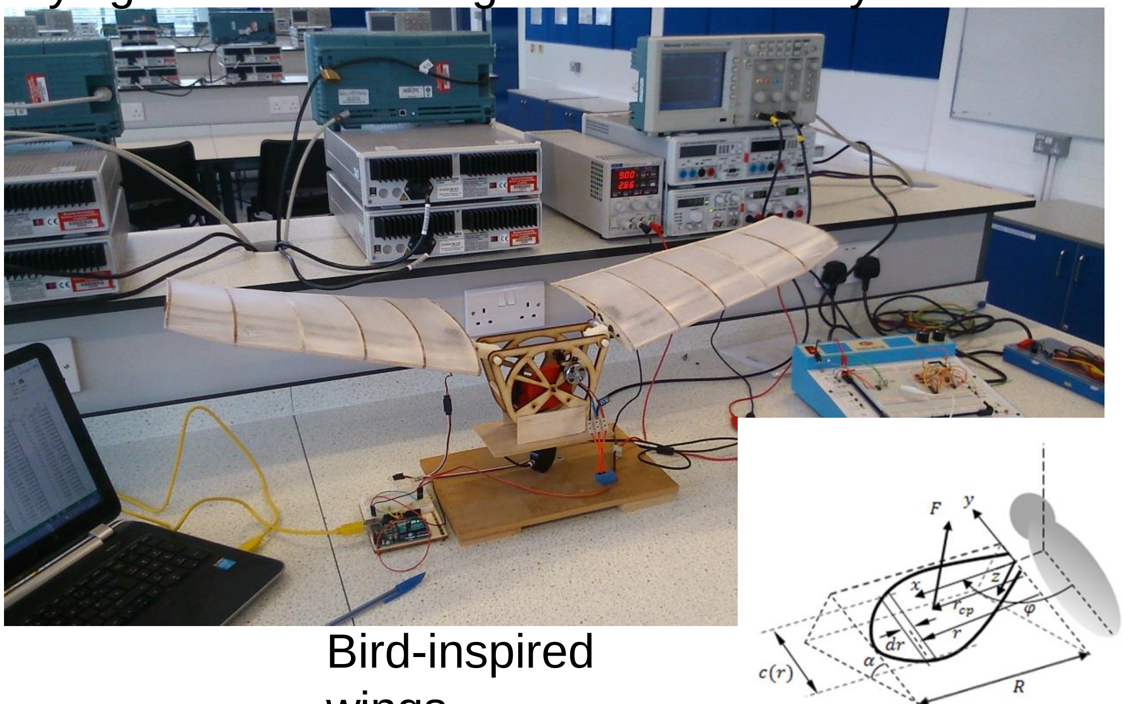




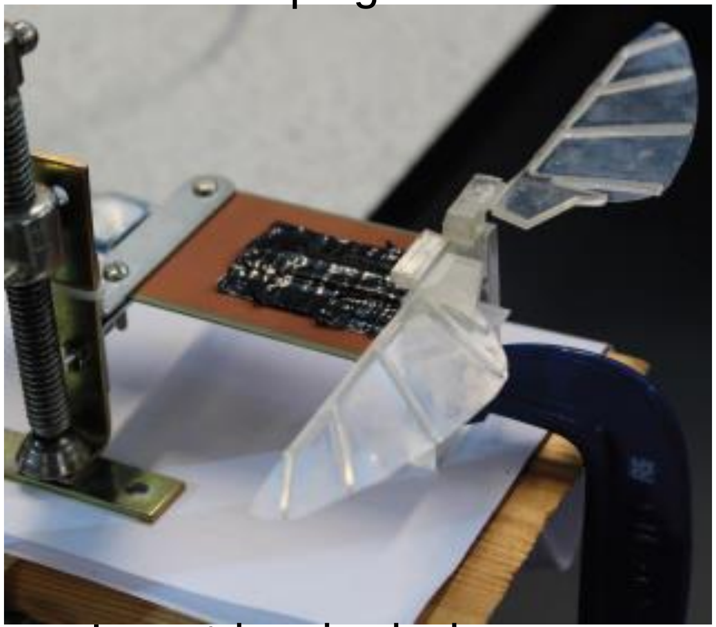
Farbod Khoshnoud, Clarence W. De Silva, et al., **Mechatronics: Fundamentals and Applications**, Taylor & Francis / CRC Press, 2015.

Bird- and insect-inspired flapping wing flying robots

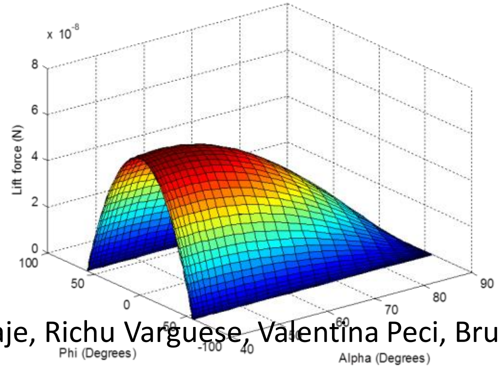
There is no fixed-wing aircraft with agility and manoeuvrability of a bird or insect.
Bird- and insect-inspired flapping wing flying robots: allows developing flying vehicles with high manoeuvrability.



Bird-inspired wings



Insect-inspired wings

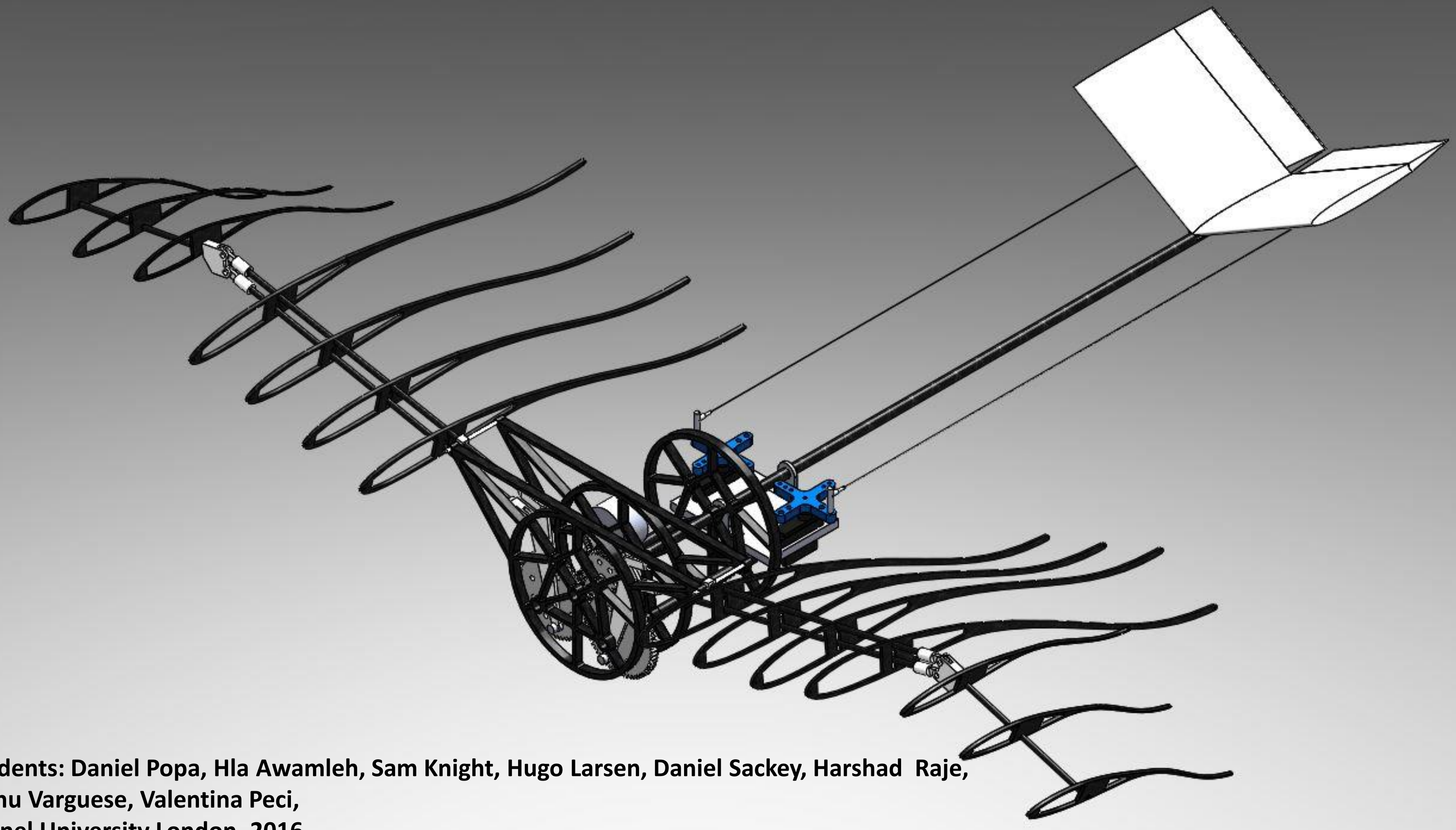


Lift force $$F_L = \frac{1}{2}\rho\bar{c}R^3 r_s \int_0^{\pi} C_{L_{max}} \sin(2\alpha(x))\, \Phi^2\omega^2 \cos^2 x\, dx$$

$$F_L = \frac{1}{2}\rho\dot{\varphi}^2 C_L(\alpha)\bar{c}R^3 \int_0^1 (\bar{r})^2\, \bar{c}(\bar{r}) d\bar{r}$$

MSc students: Daniel Popa, Hla Awamleh, Sam Knight, Hugo Larsen, Daniel Sackey, Harshad Raje, Richu Varguese, Valentina Peci, Brunel Uni.

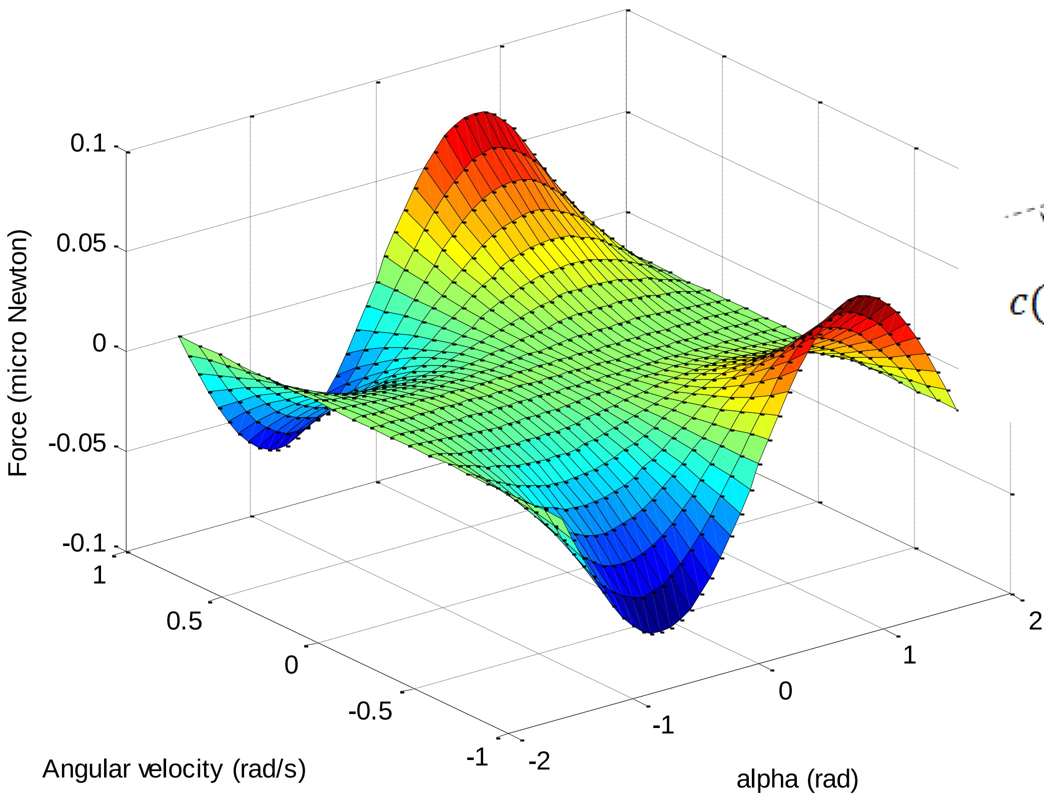
Bio-inspired flying vehicles

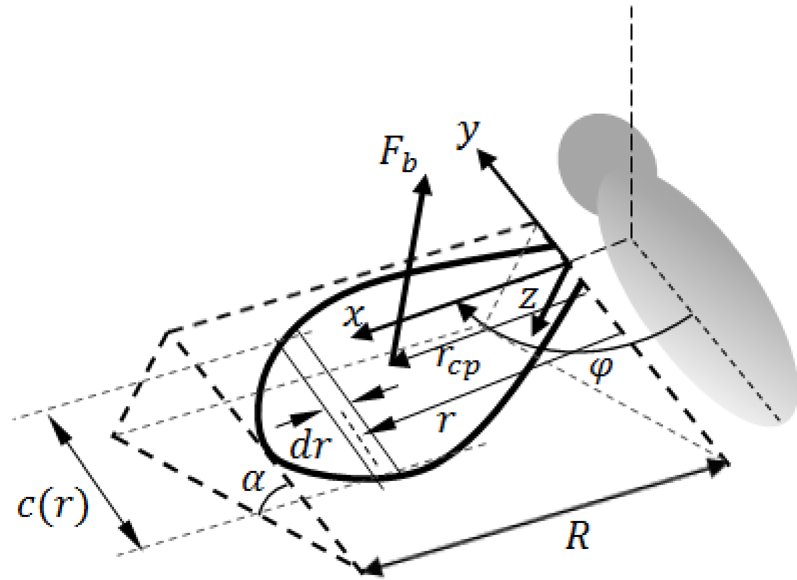


Students: Daniel Popa, Hla Awamleh, Sam Knight, Hugo Larsen, Daniel Sackey, Harshad Raje, Richu Varguese, Valentina Peci,
Brunel University London, 2016.

Dynamics and Control of bio-inspired flapping wing robots as flying vehicles

$$F_L = \frac{1}{2}\rho\dot{\varphi}^2 C_L(\alpha)\bar{c}R^3 \int_0^1 (\bar{r})^2\,\bar{c}(\bar{r})\,d\bar{r}$$



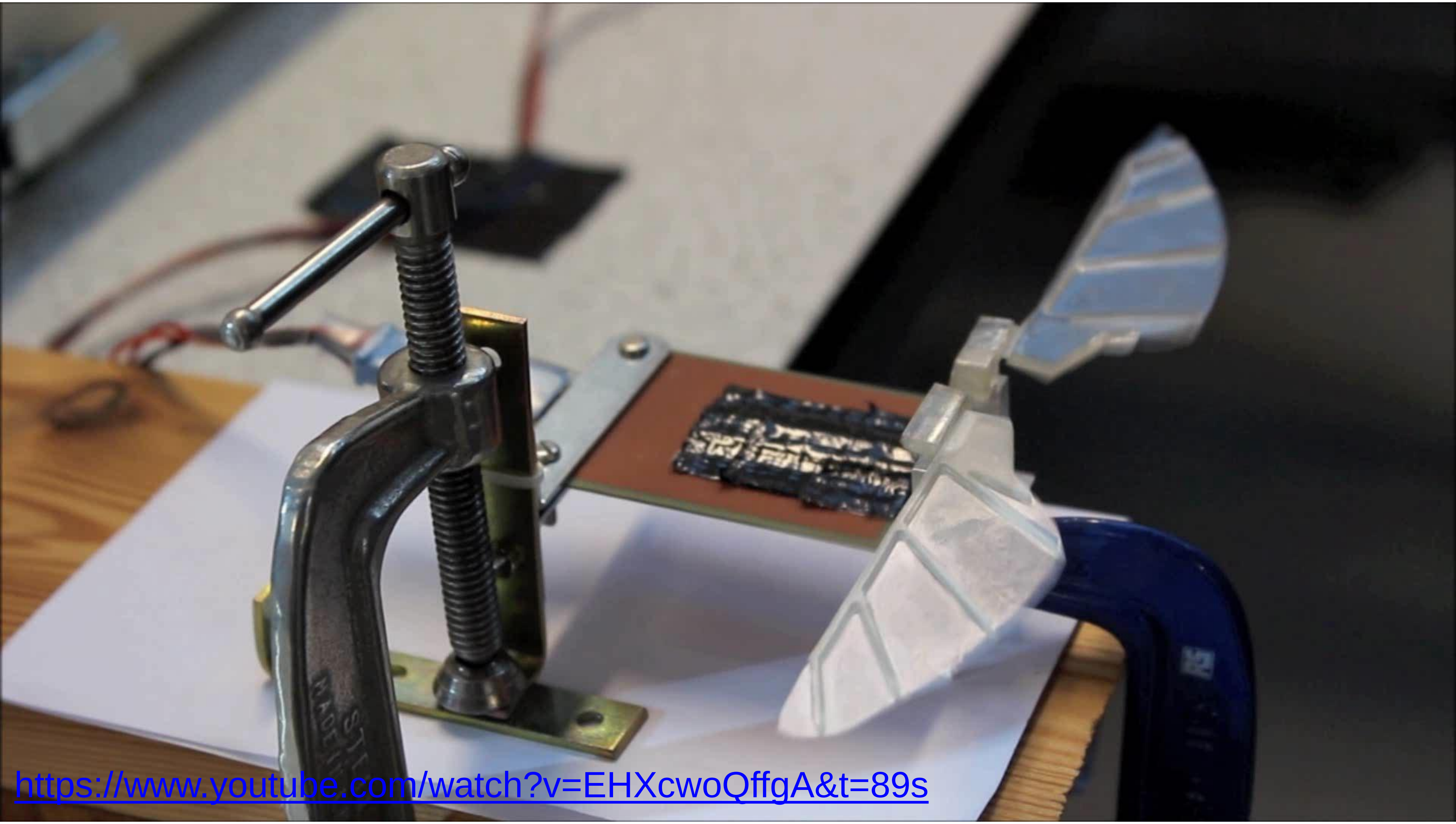


$$dF = \frac{1}{2}\rho\dot{\varphi}^2 r^2 C_F(\alpha)c(r)dr$$

Proposal to: H2020

Insect-inspired flapping wing Micro Air Vehicles:

Piezoelectric actuation and flexible hinge mechanisms



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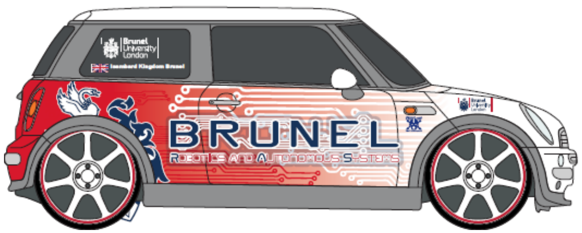
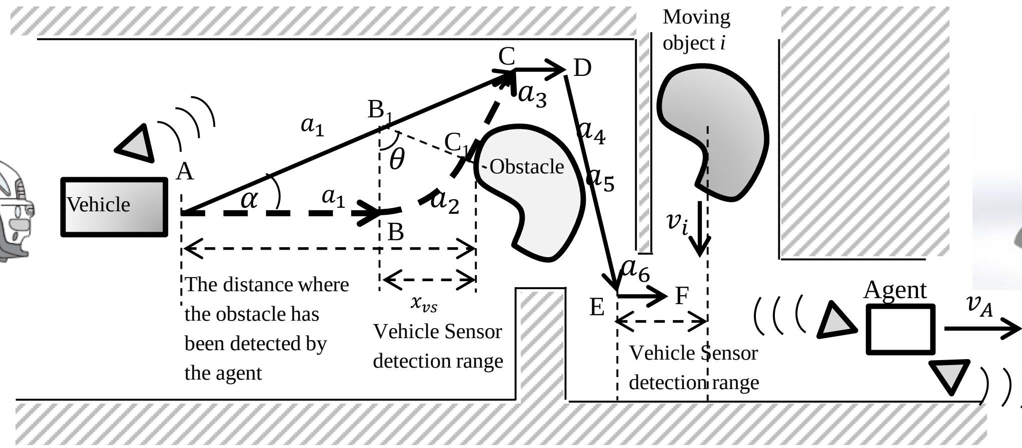
MSc Student: Hugo Larsen, 2015

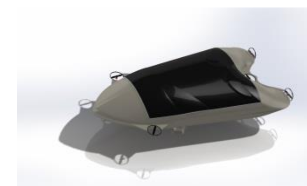
Video Link

Autonomous/Self-Driving Vehicles projects

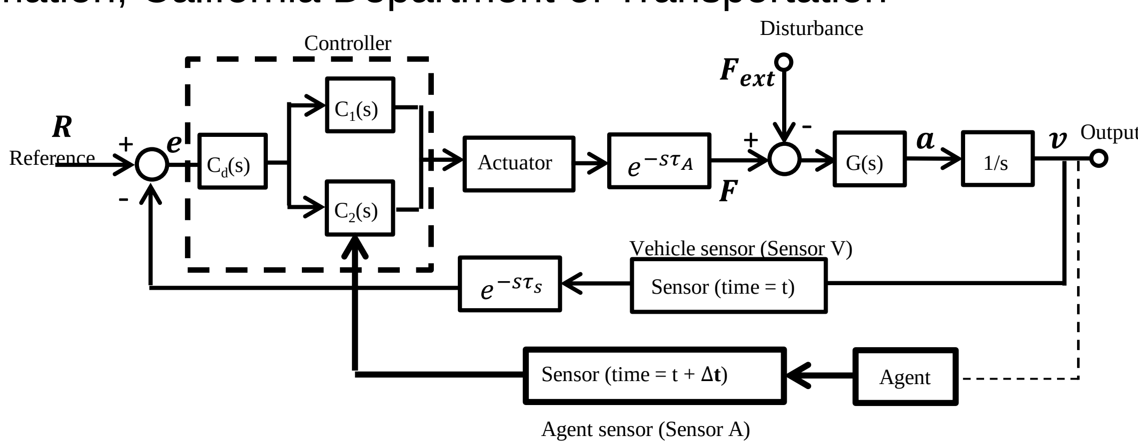
Bioinspired Psi Intelligent Control for Autonomous Systems.







“Caltrans is currently working on a policy with respect to UAVs in the Right-of-Way”, ITS Special Projects Office of Traffic Operations Research, Division of Research, Innovation and System Information, California Department of Transportation



Farbod Khoshnoud, Clarence W. De Silva, Ibrahim Esat, **Bioinspired Psi Intelligent control for autonomous dynamic systems**, Journal of Control and Intelligent Systems, Vol. 43, No. 4, 2015.

Nature-inspired Quantum Entanglement of Autonomous Systems

Quantum Cooperation of Two Insects

By Johann Summhammer, Vienna University of Technology

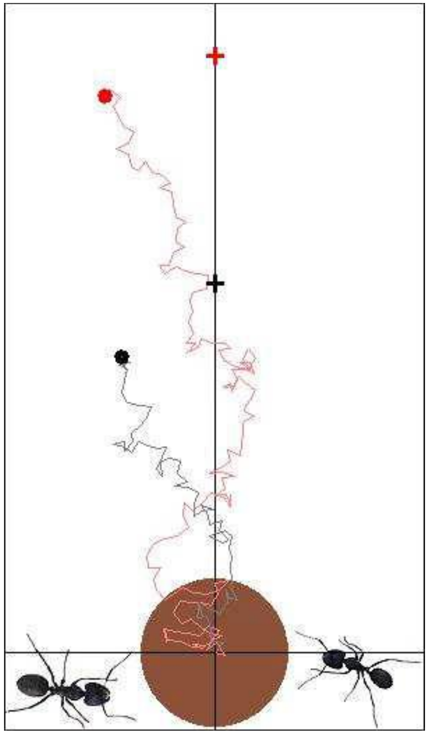


Figure: Typical stochastic paths of the pebble as pushed by quantum entangled ants (red) as well as by independent ants (black).

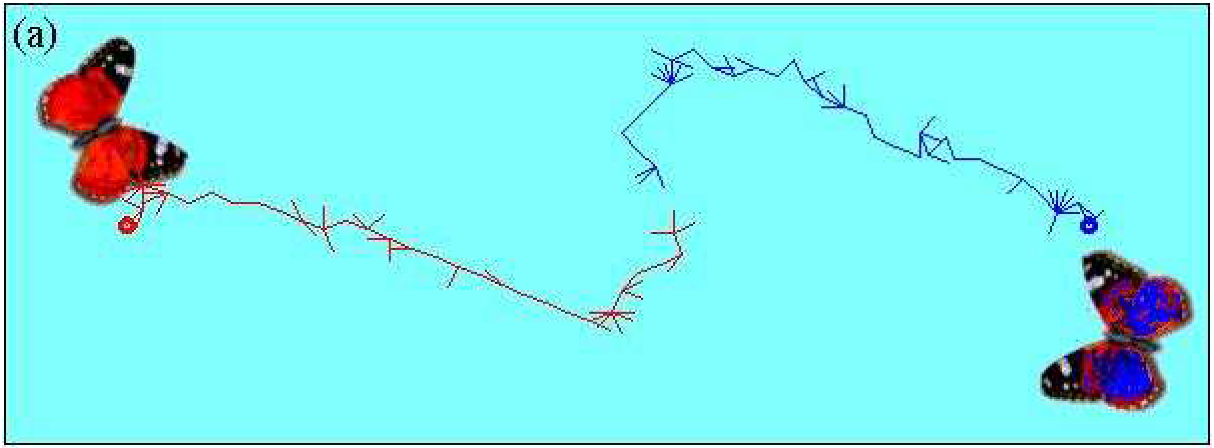


Figure: (a): Typical flight paths of the two butterflies. (b): The quantum entangled butterflies needed an average of 2778 short flights to find each other, versus 5255 short flights for the independent butterflies.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security

Singlet state

$$|\psi\rangle_s = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$p_{\uparrow\uparrow}^{(s)} = p_{\downarrow\downarrow}^{(s)} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

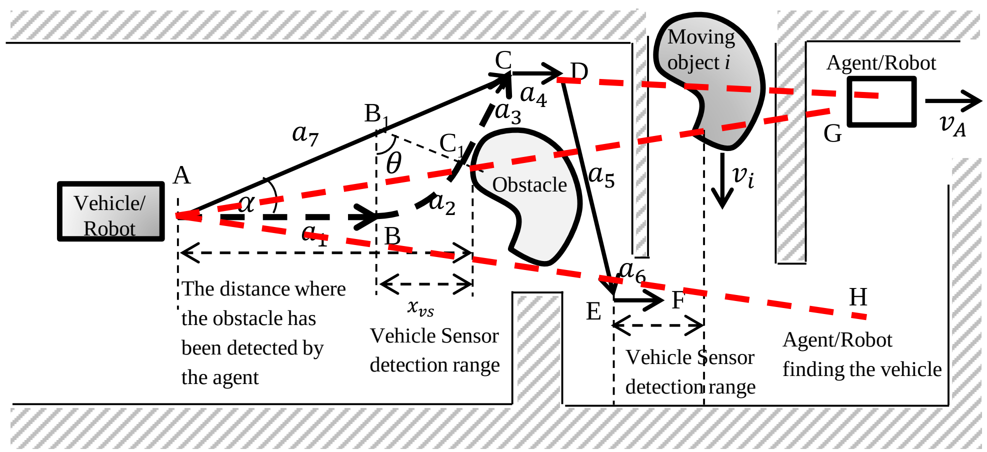
$$p_{\uparrow\downarrow}^{(s)} = p_{\downarrow\uparrow}^{(s)} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

Triplet state

$$p_{\uparrow\uparrow}^{(t)} = p_{\downarrow\downarrow}^{(t)} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

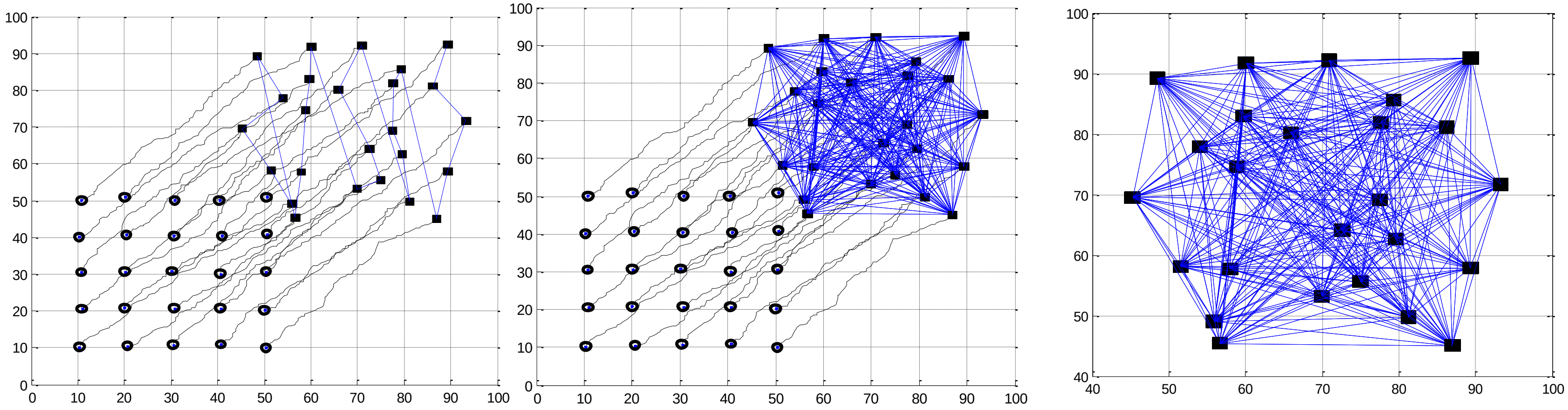
$$p_{\uparrow\downarrow}^{(t)} = p_{\downarrow\uparrow}^{(t)} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

- *Choose a random direction for a task (e.g., moving, applying force).*
- *The probability of random directions can be enhanced via probability weight factors for "suitable" directions.*
- *Decide to perform the task by the quantum measurement of the spin of the particle (for the vehicle/robot) reserved for this direction.*



Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Network of Autonomous Vehicles for Cyber-physical security

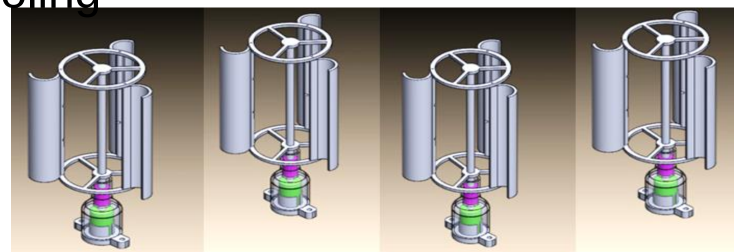


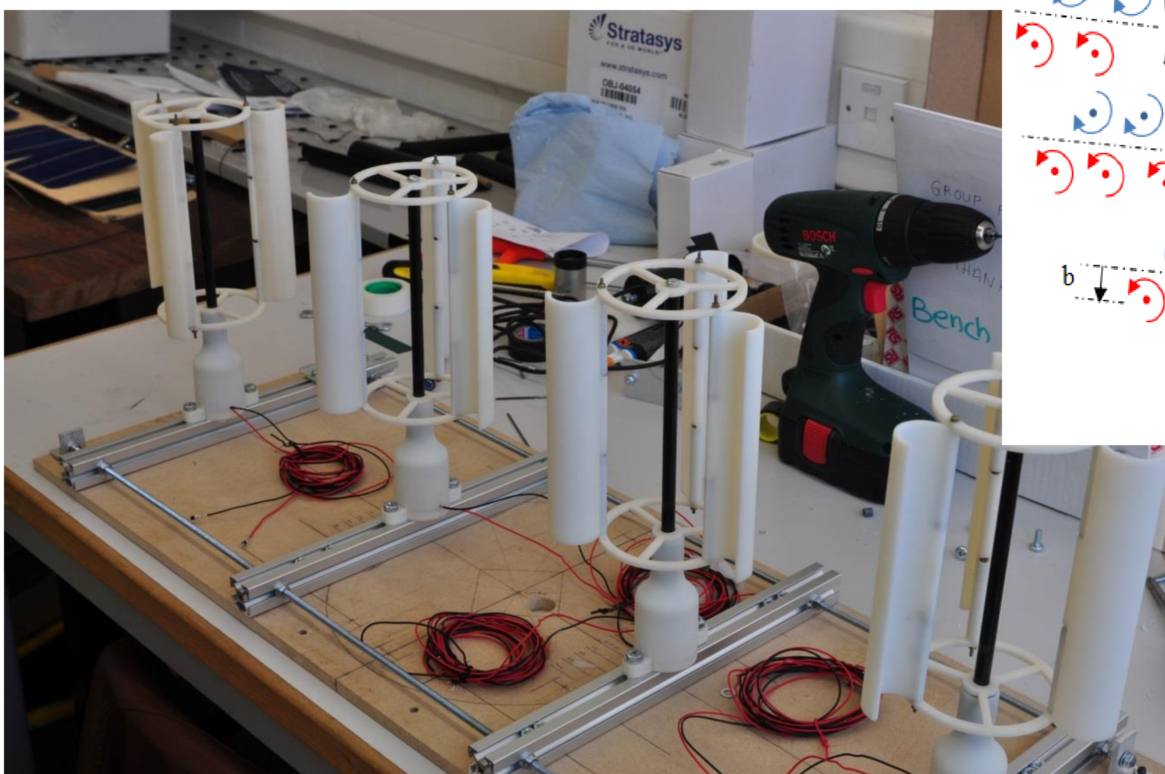
- **25 UVs at the starting locations at the nodes are shown with circles**
- **Final positions of the UVs are shown by the filled squares**
- **The trajectories of the UVs are shown from each initial location to the final position**
- **Horizontal and vertical axes represent x and y coordinates associated with the two dimensional motion.**

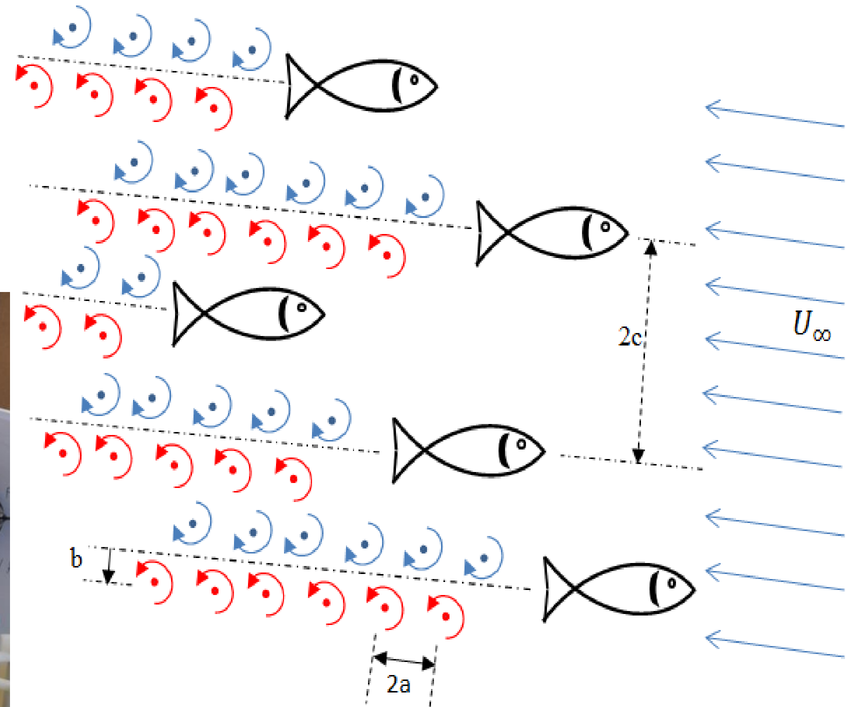
Farbod Khoshnoud, I.I. Esat, C.W. De Silva, M.B. Quadrelli, **Quantum Network of Cooperative Unmanned Autonomous Systems**, *Unmanned Systems journal*, Vol. 07, No. 02, pp. 137-145 (2019).

Bio-inspired Vertical Axis Wind Turbines

Improving the power density of vertical axis wind turbines inspired by fish schooling

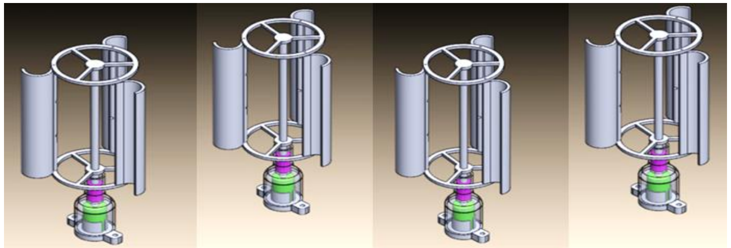


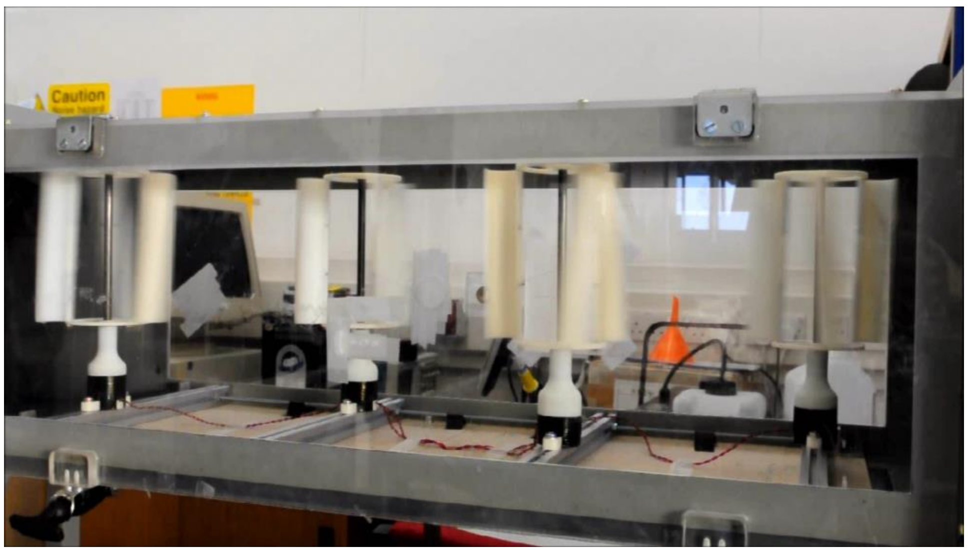


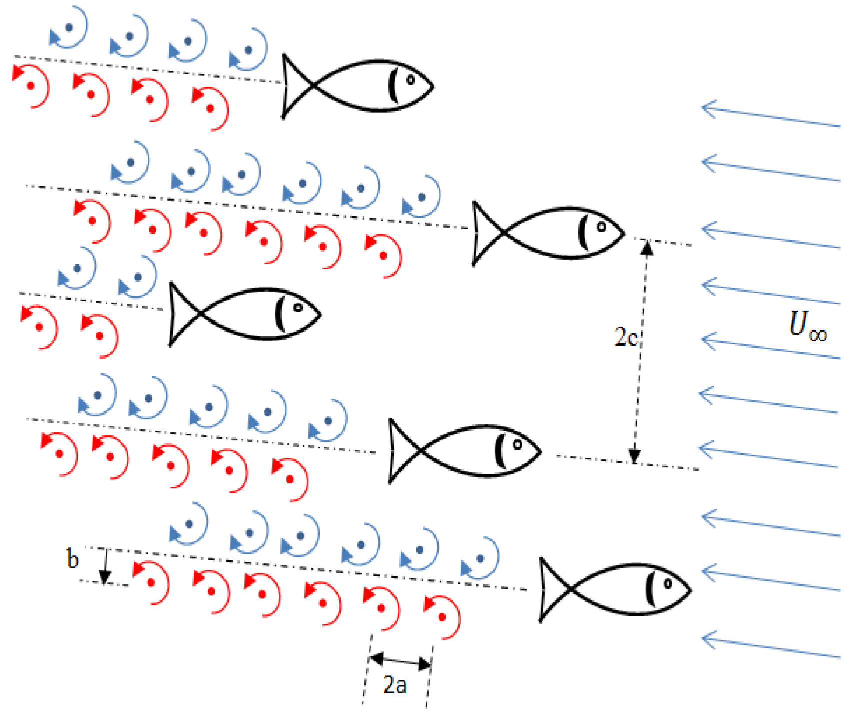


MEng students:
Ahmad Abdullah, Muhammad Asa Ri, Siti Razali, Nuramira Khairuddin, Amirul Ahmad Norizan, Nurul Suhaimi

Bio-inspired Vertical Axis Wind Turbines







Video Link

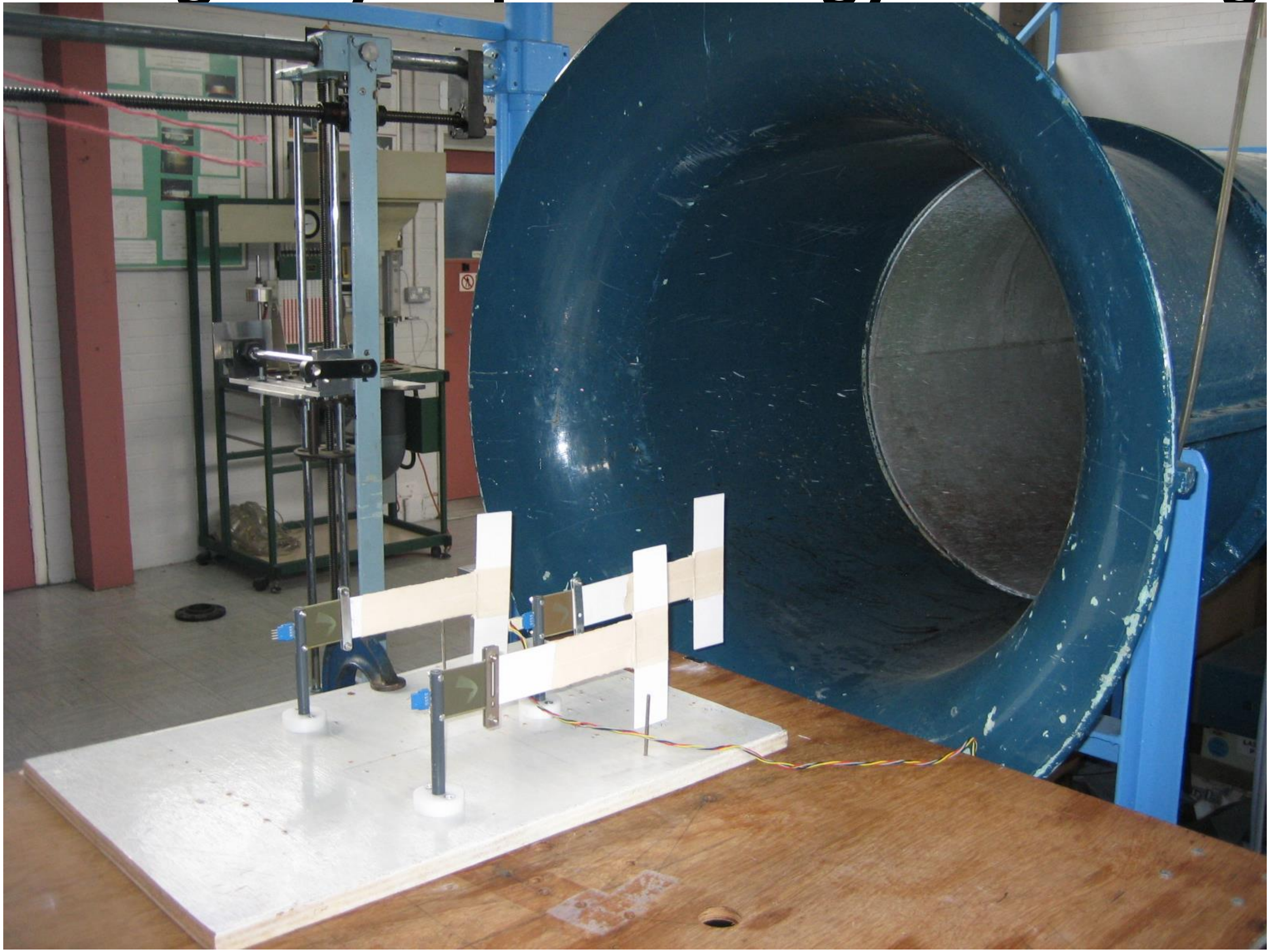
MEng Students: Ahmad Mustaqim Abdullah, Nurul Sofia Suhaimi, Siti Nuraisyah Razali, Nuramira Khairuddin, Muhammad Harith Asari, Amirul Norizan

Farbod Khoshnoud, M. M. McKerns, C. W. De Silva, I. I. Esat, R. H.C. Bonser, H. Owhadi, **Self-powered and Bio-inspired Dynamic Systems: Research and Education**, ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, Arizona, USA, 2016.

Biologically Inspired Systems: Piezoelectric Energy Harvesters

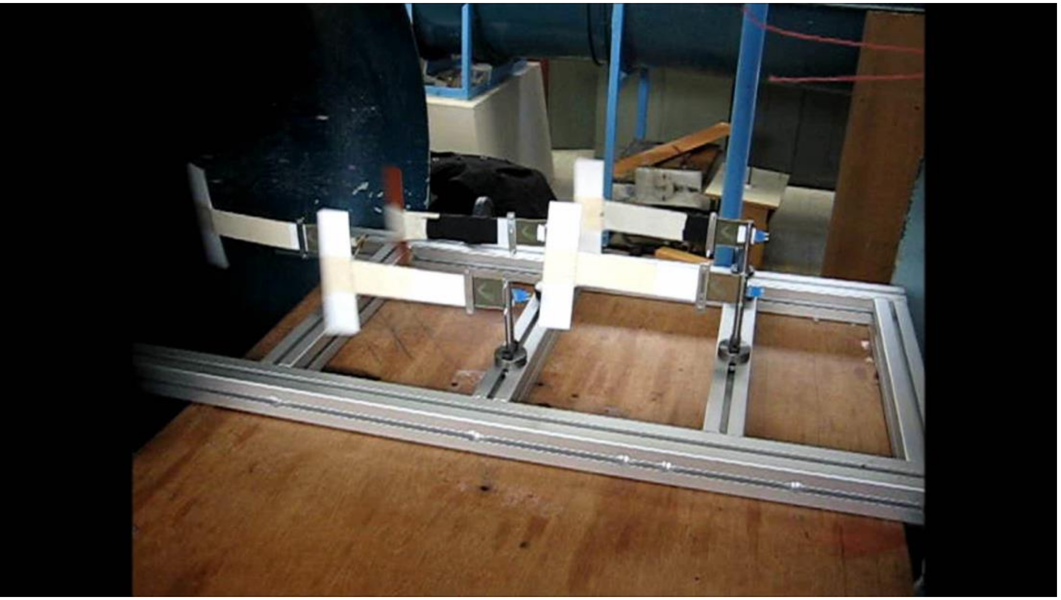
Video Link

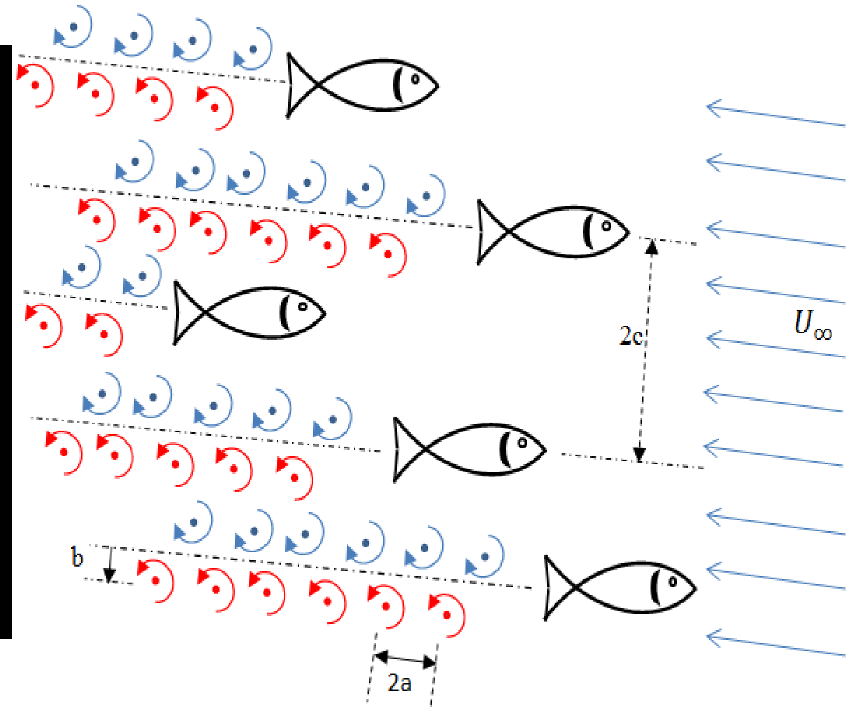
Biologically Inspired Energy Harvesting



Farbod Khoshnoud, Dario Robinson (Pomona Police), Ibrahim I. Esat (Brunel), Clarence W. De Silva (UBC), Richard H.C. Bonser (Brunel), Marco B. Quadrelli (JPL), **Research-informed service-learning in Mechatronics and Dynamic Systems**, *American Society for Engineering Education conference*, Los Angeles, April 4-5, 2019, Paper ID #27850, [PDF].

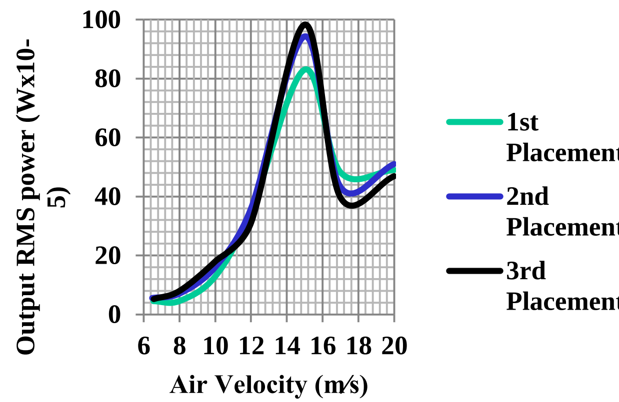
Bio-inspired Piezoelectric Energy Harvesters



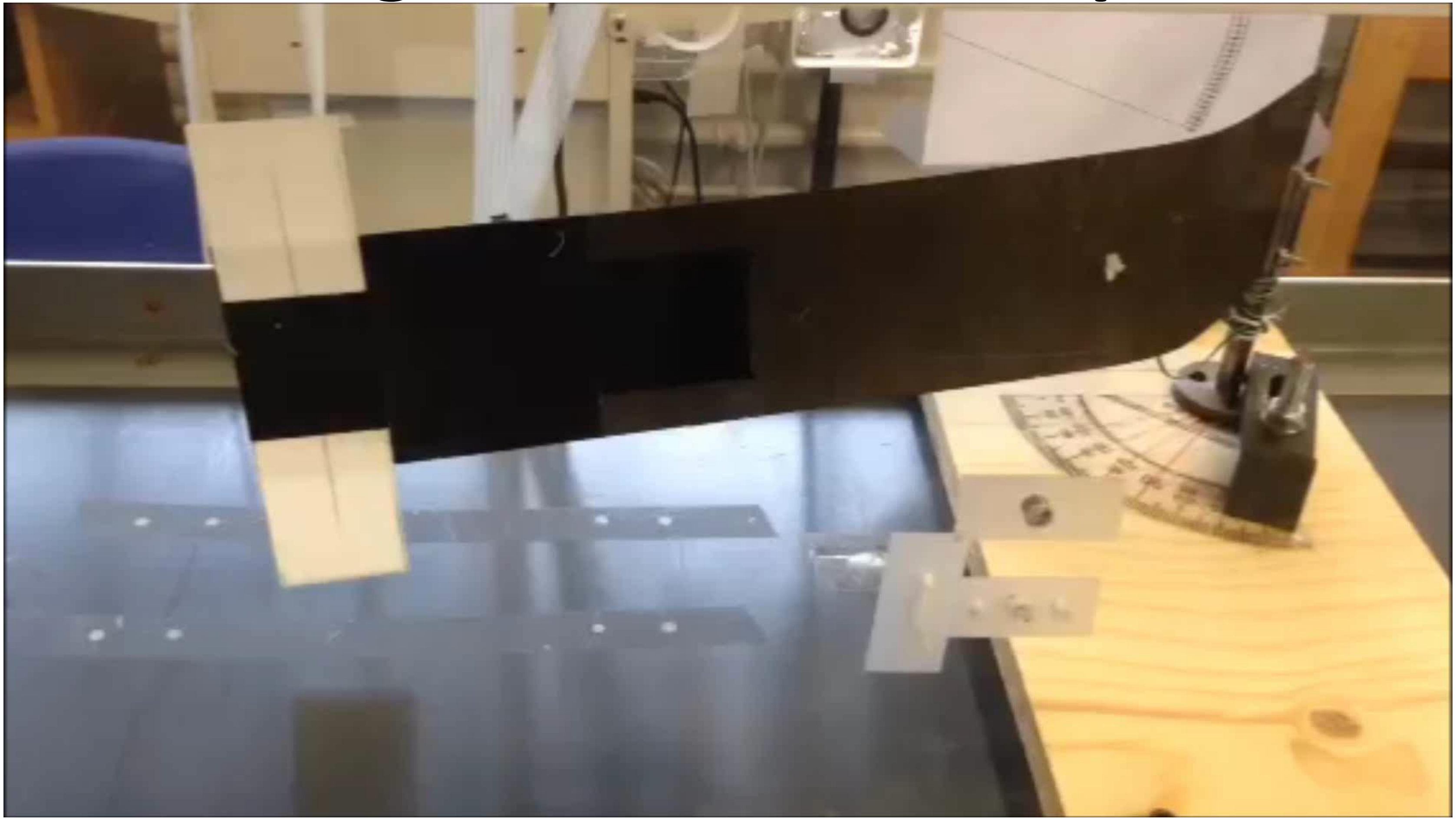


Video Link

Farbod Khoshnoud, A. Shahba, O. Riaz, R. Shah, R. Shimura, Y. K. Chen and G. Gaviraghi, **Piezoelectric energy harvesting for airships and investigation of bio-inspired energy harvesters**, 5th European Conference for Aeronautics and Space Sciences, Munich, Germany, 1-5 July 2013.



Bistable piezoelectric energy harvesting – Wind tunnel experiment



Farbod Khoshnoud, Christopher Bowen (Bath), Cris Mares (Brunel), **Bistable Piezoelectric Flutter Energy Harvesting with Uncertainty Analysis**, *Instrumentation Journal*, Vol 6. No 1, 2019.

Video Link

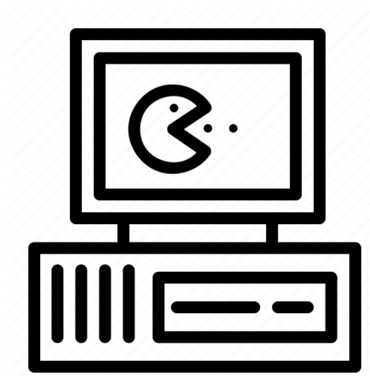
- Self-powered Dynamic Systems
- Nature/Bio-inspired Dynamic Systems
- Quantum Multibody Dynamics, Robotics, and Autonomy
- Optimal Uncertainty Quantification for engineering Systems

Mechanical Systems + Classical Computers

Mechanical Systems

+

Classical Computers/Technologies



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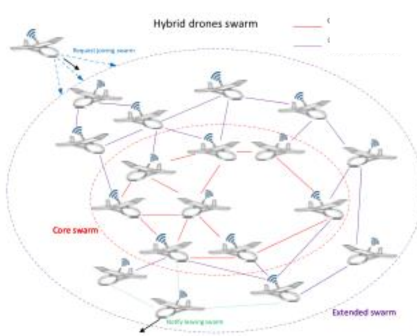
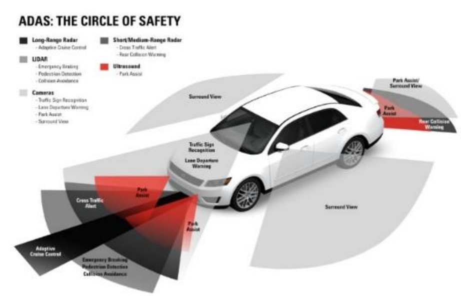
The State-of-the-art



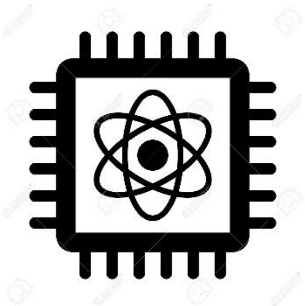


Mechanical Systems + Quantum Technologies

Current Mechanical Systems

+

Quantum Technologies



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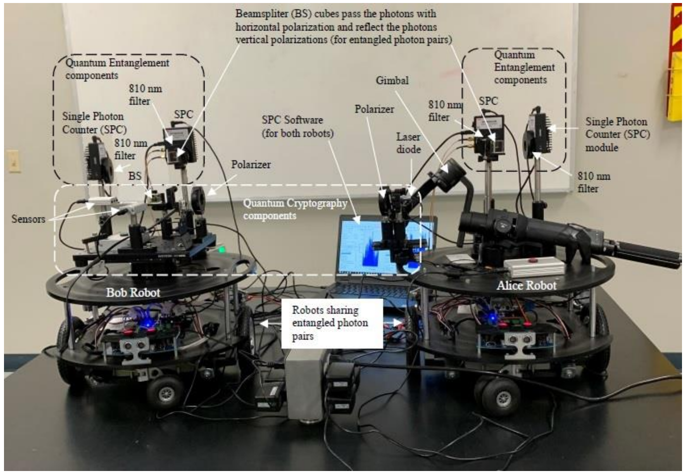
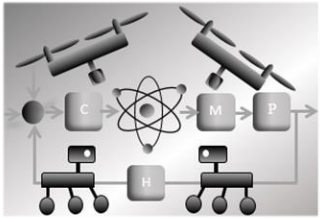
Quantum Robotics and Autonomy (e.g., The Alice and Bob Robots)





Quantum Robotics and Autonomy

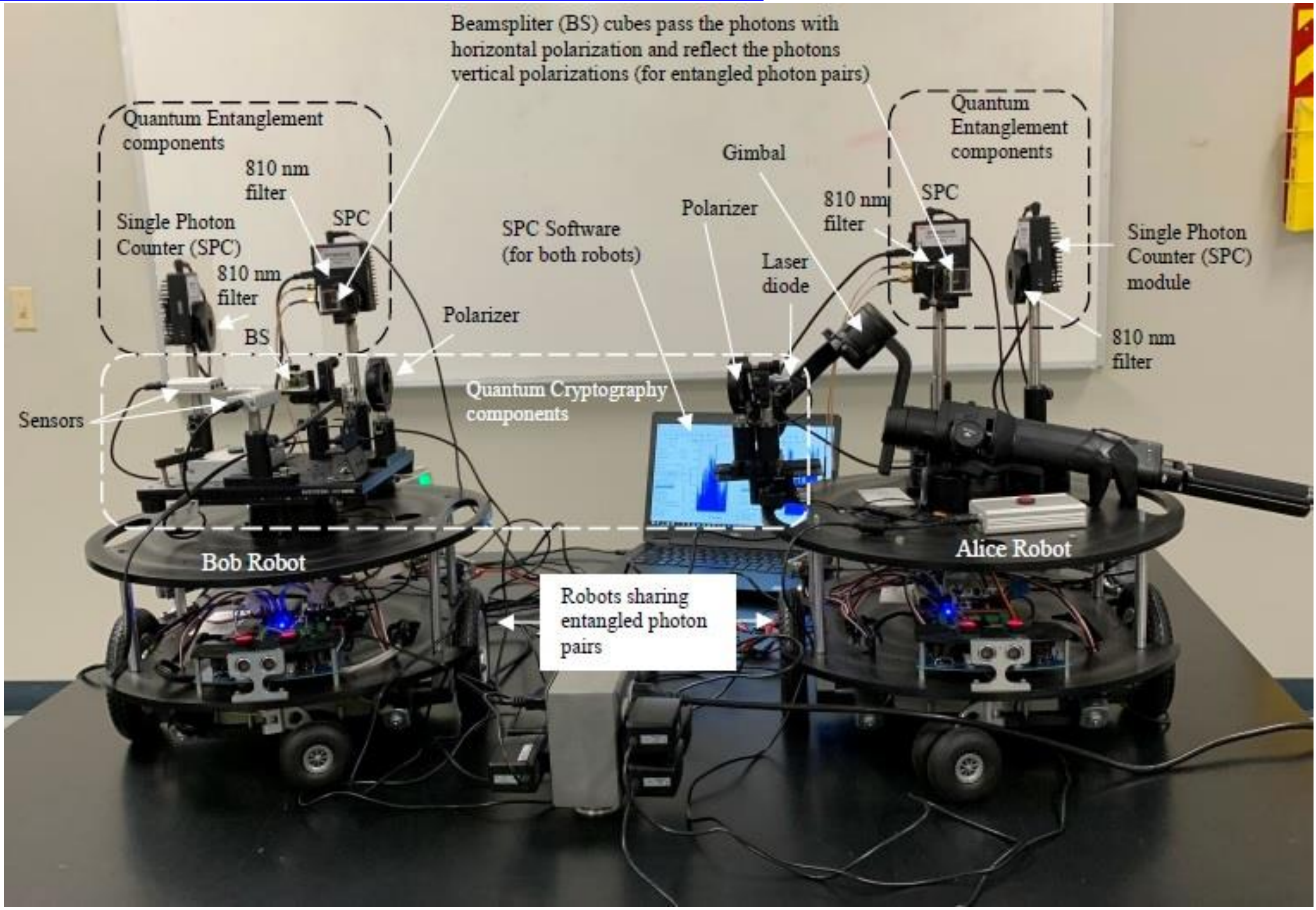
Integrating Quantum Technologies with physical Engineering Systems (at macroscale)

Pushing the engineering boundaries beyond classical techniques

Quantum Multibody Dynamics Initiative: Pushing the engineering boundaries beyond existing techniques

https://www.youtube.com/watch?v=ForcnzWzG1M&t=

- Implementing Experimental **Quantum Entanglement** for Robots (robots to share entangled photons) to utilize and enable quantum entanglement, "**spooky action at a distance**", for cooperative autonomy.
- Accessing guaranteed security for cooperative autonomy by **Quantum Cryptography**.
- **Quantum Teleportation** for communications in between multi-agent autonomous systems by teleporting quantum states.



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal, Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

F. Khoshnoud, I. I. Esat, M. B. Quadrelli, D. Robinson, **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal, Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]

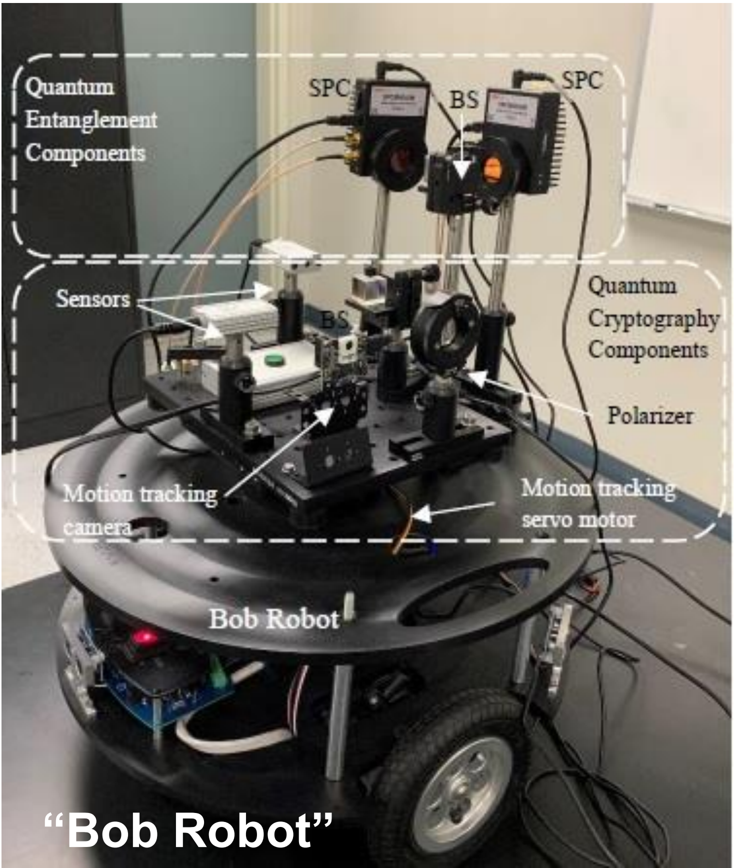
Integration of Quantum Technologies with Engineering Systems to Access Quantum Supremacy at Macroscale

Quantum Entanglement, Cryptography, and Teleportation For Control of Dynamical Systems and Autonomy

"Alice Drone"

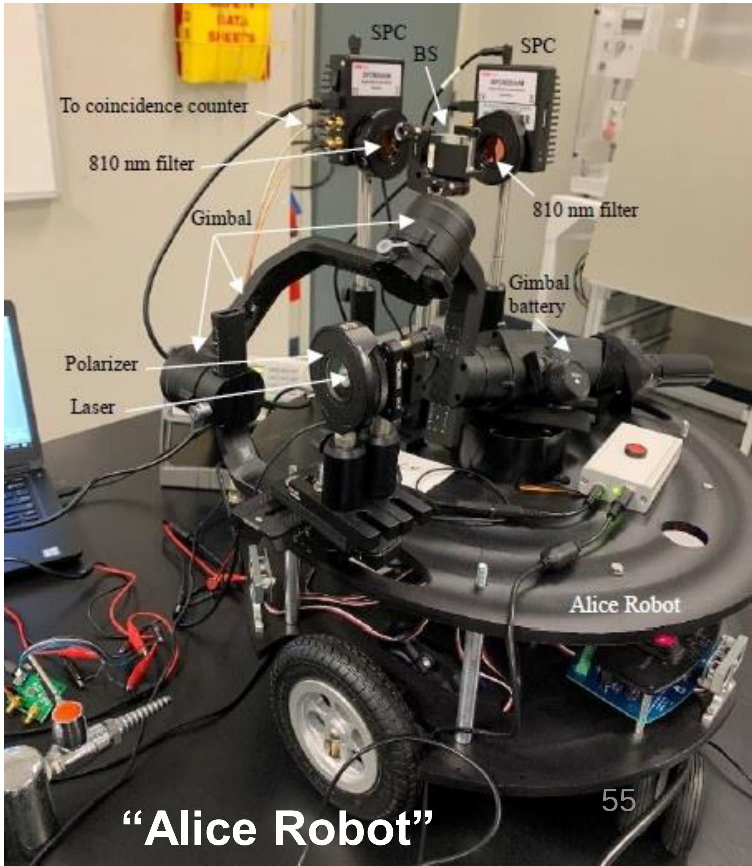
- Polarizations of the entangled photons will be converted to classical digital information for digital control and autonomy applications,
- or in case of accessing quantum computers in future, will be used directly by quantum computers* for autonomy

*in fact, using any classical transfer of information between robots equipped with quantum processors/computers (when quantum computers become available in future) can actually defeat the advantage of quantum computers.



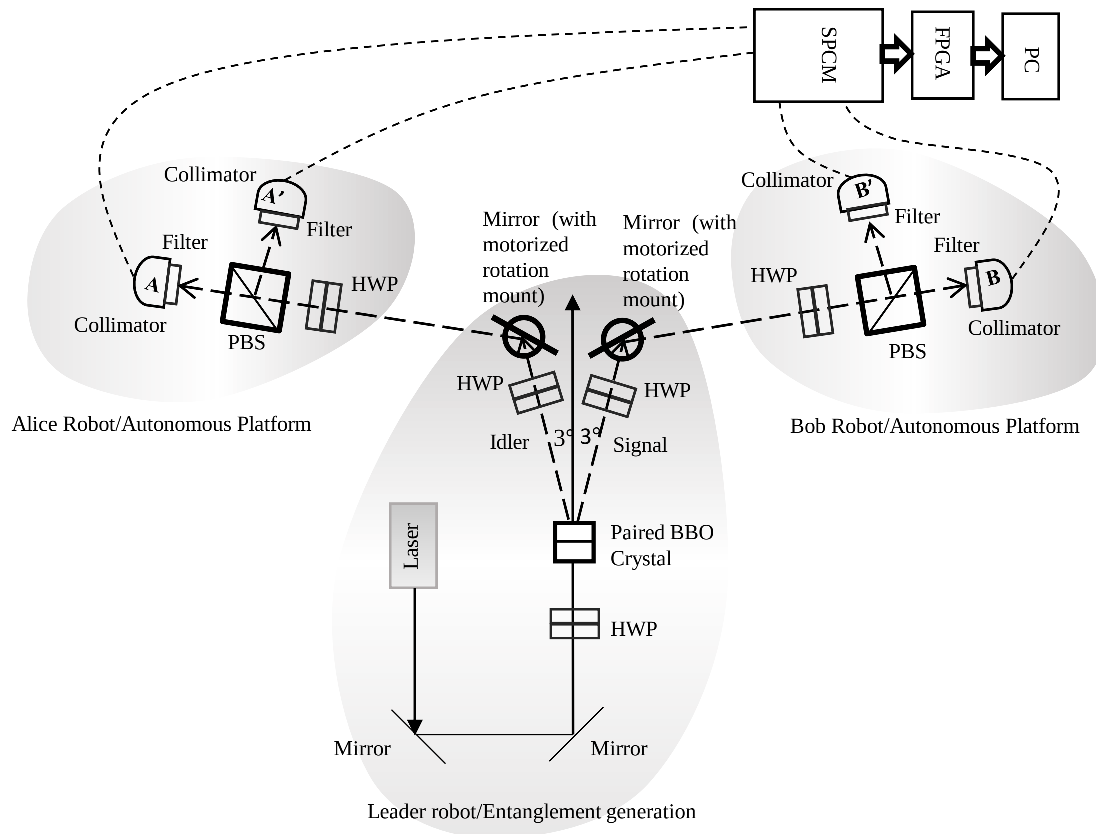
Entangled Photons are generated by 'Spontaneous Parametric Down Conversion', and sent to Alice and Bob Robots

Quantum Entangled Photons will be received by the Single Photon Counter (SPC) modules placed on the robots



Quantum Entanglement Experiment

- SPDC Process
- Nonlinear BBO crystal
- 405 nm source
- 810 nm PBS, and HWPs
- 10 nm bandwidth filters
- 4-Channel SPCM
- Single photon counter FPGA



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

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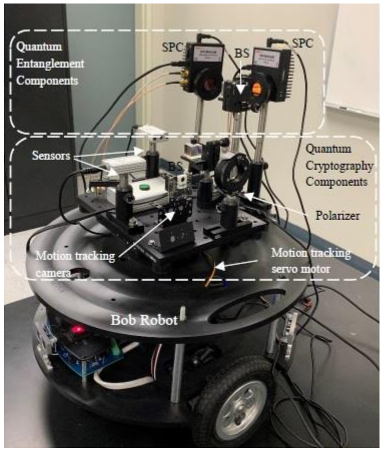
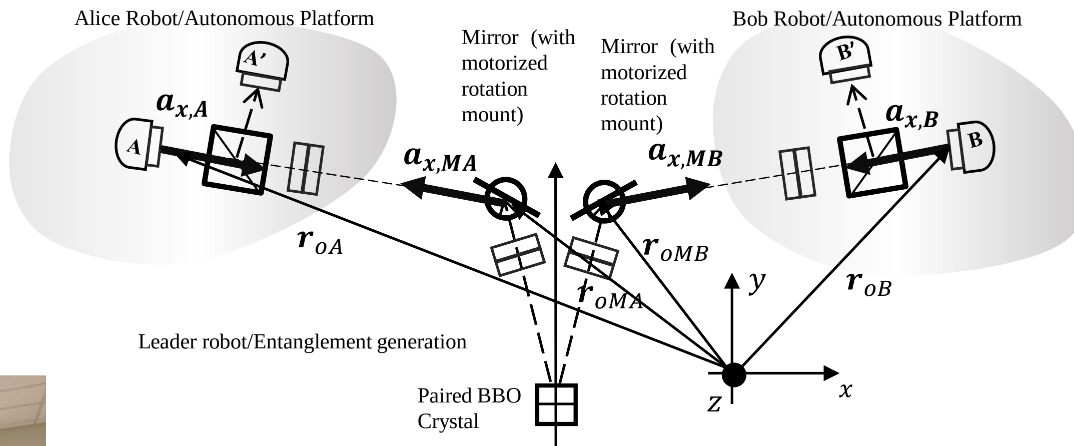
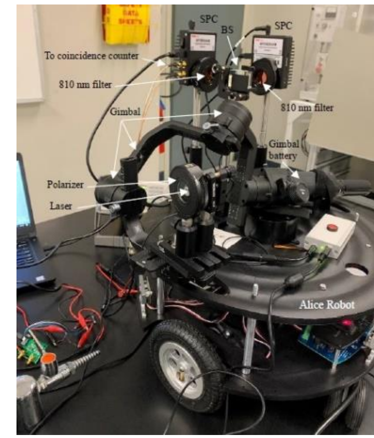
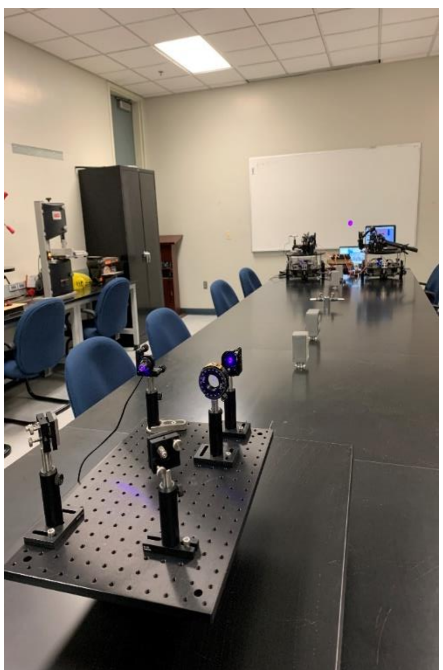
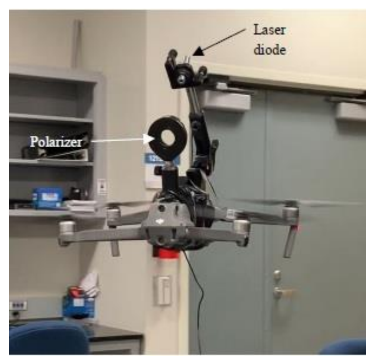
Quantum Entanglement Experiment
Automated alignment for mobile agents





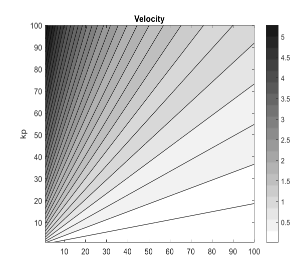




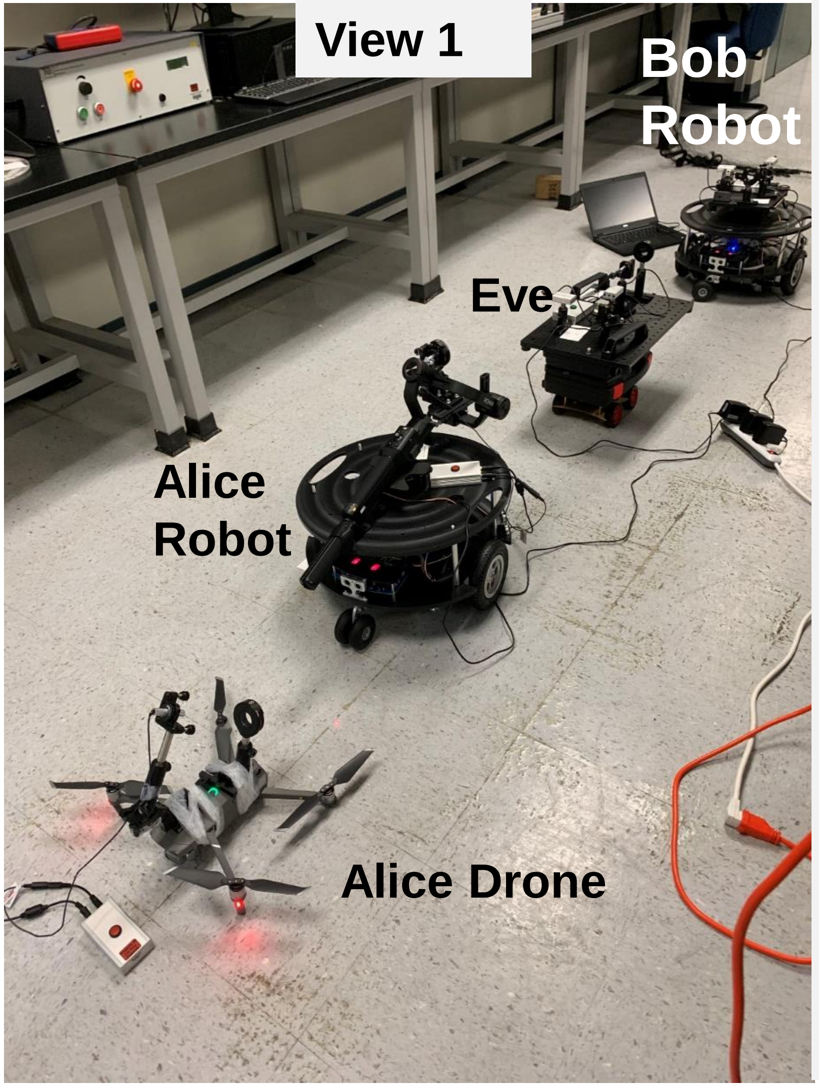


$$\mathbb{P}[P(X) > dia_{collimator}] \leq \epsilon$$

$$\boldsymbol{v_B} \in \boldsymbol{\mathcal{X}}_3 := [\boldsymbol{v}_{\boldsymbol{B}_{min}}, \boldsymbol{v}_{\boldsymbol{B}_{max}}] \text{ m}/s$$

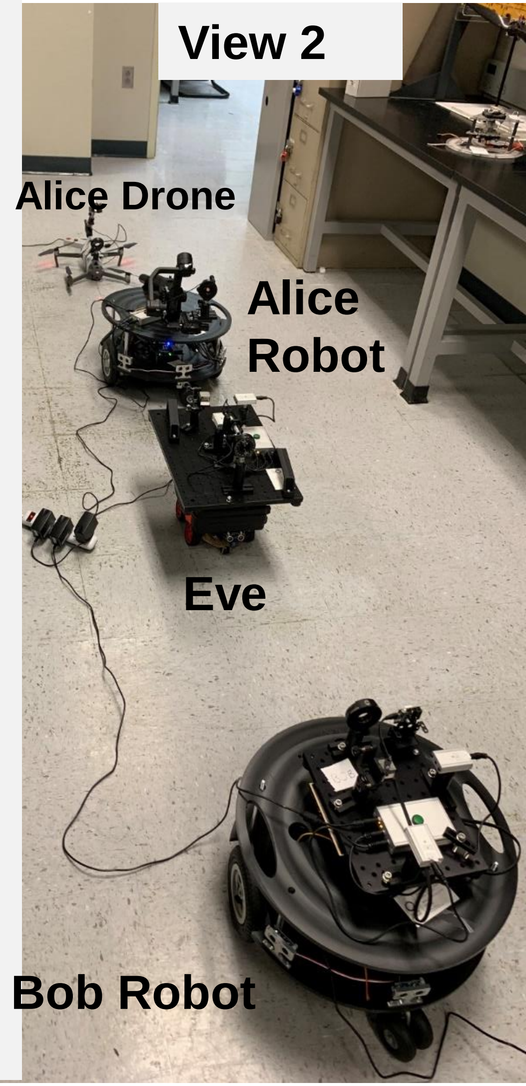


F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]
F. Khoshnoud, M. Ghazinejad, **Automated quantum entanglement and cryptography for networks of robotic systems**, IEEE/ASME, submitted.



Quantum Cryptography for Robotics and Autonomy

Alice or Bob can be Ground or Aerial Robotics (depending on the application)

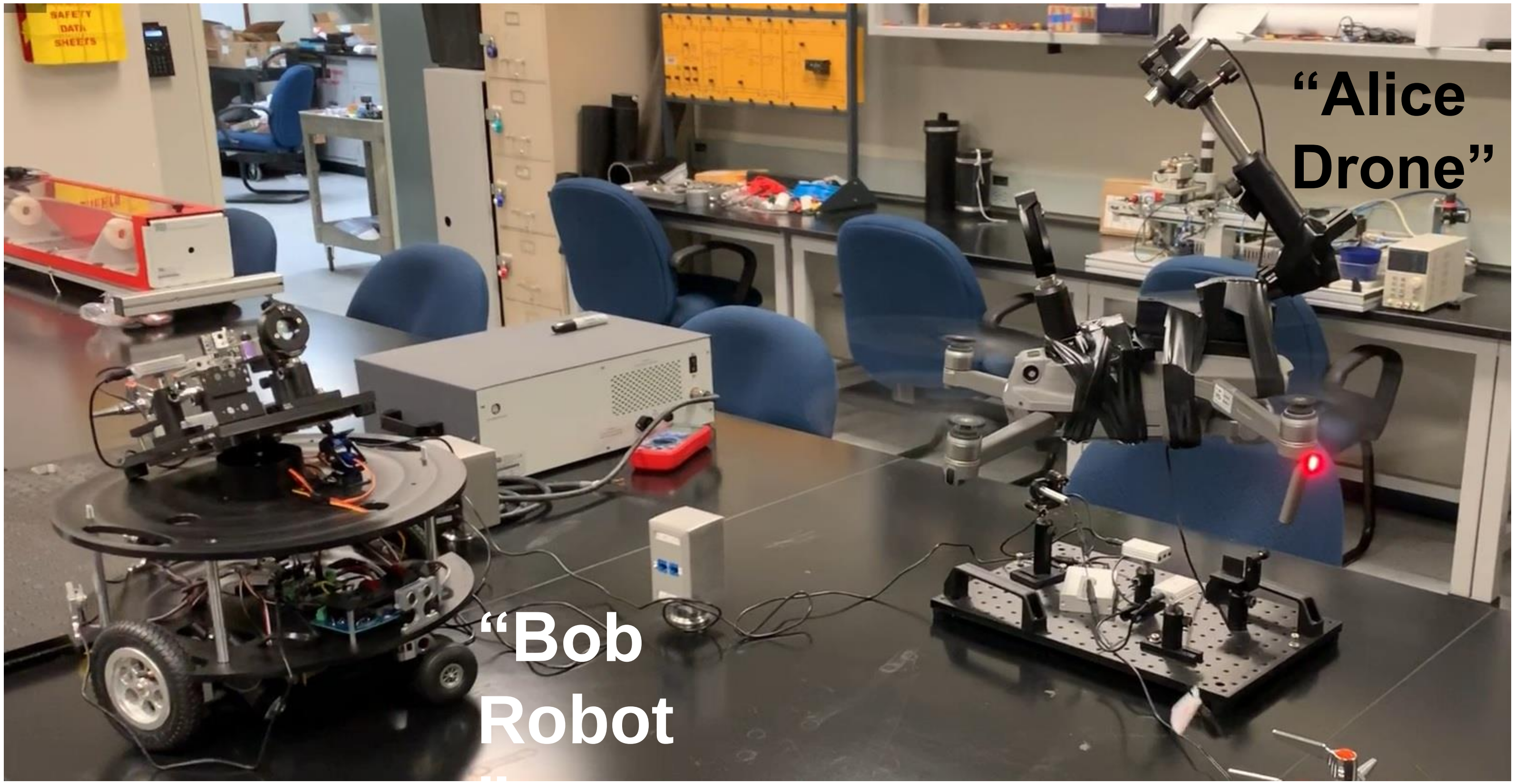


F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

F. Khoshnoud, I. I. Esat, M. B. Quadrelli, D. Robinson, **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]

Quantum Cryptography for Robotics and Autonomy



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

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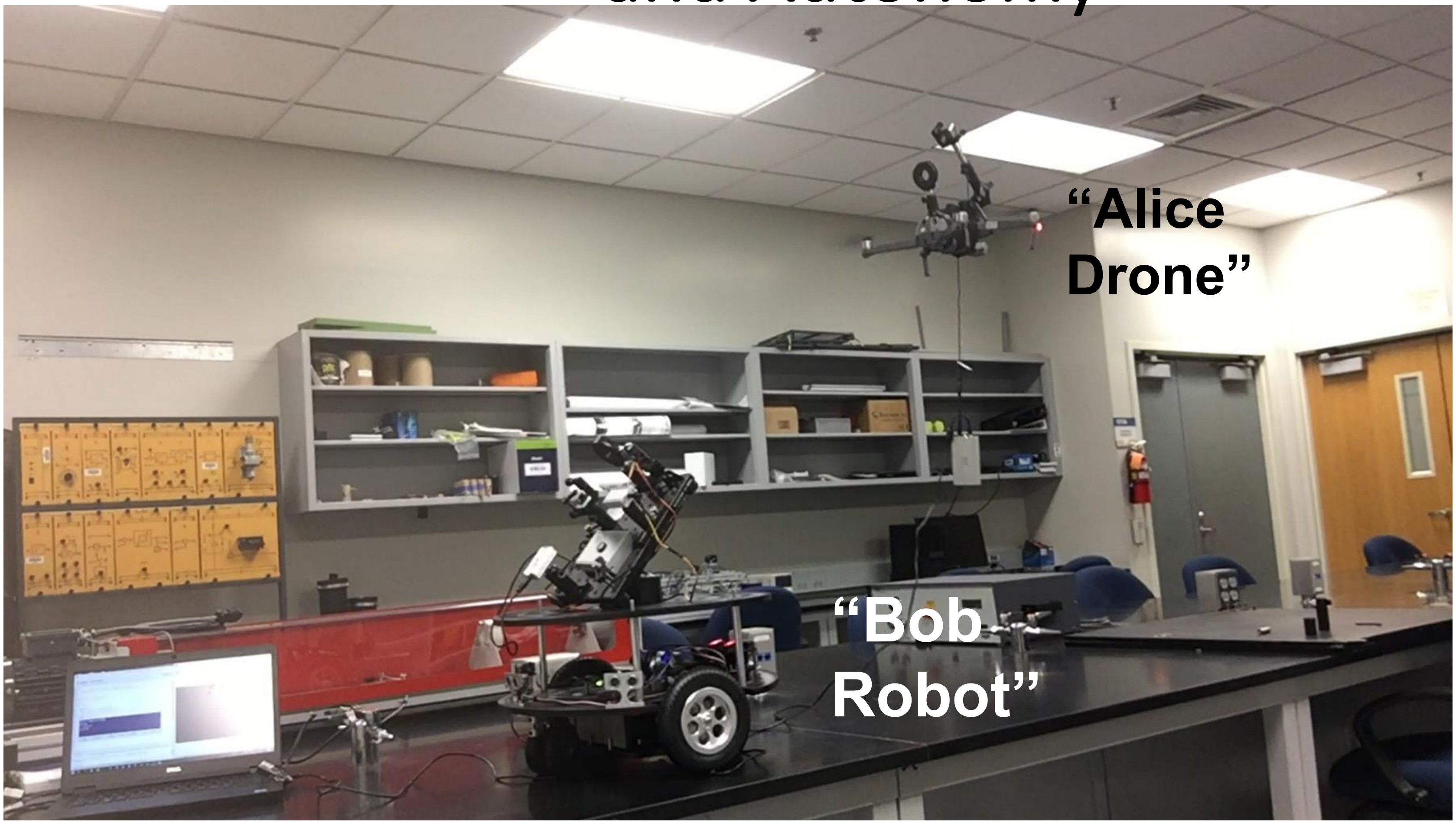
Quantum Cryptography for Robotics and Autonomy



F. Khoshnoud, L. Lamata, C. W. De Silva, M. B. Quadrelli, **Quantum Teleportation for Control of Dynamic Systems and Autonomy**, *Journal of Mechatronic Systems and Control*, 2020, in press. [Preprint PDF]

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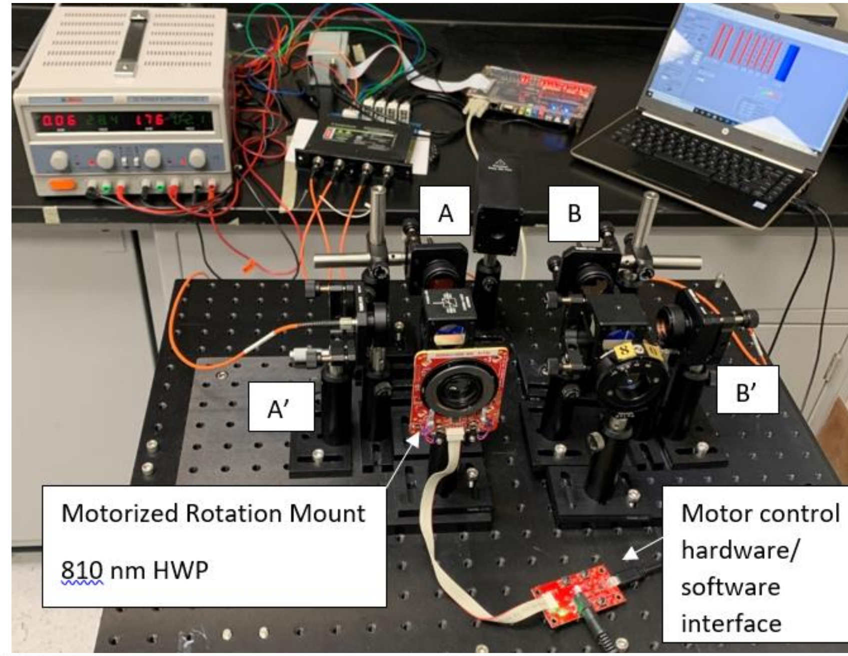
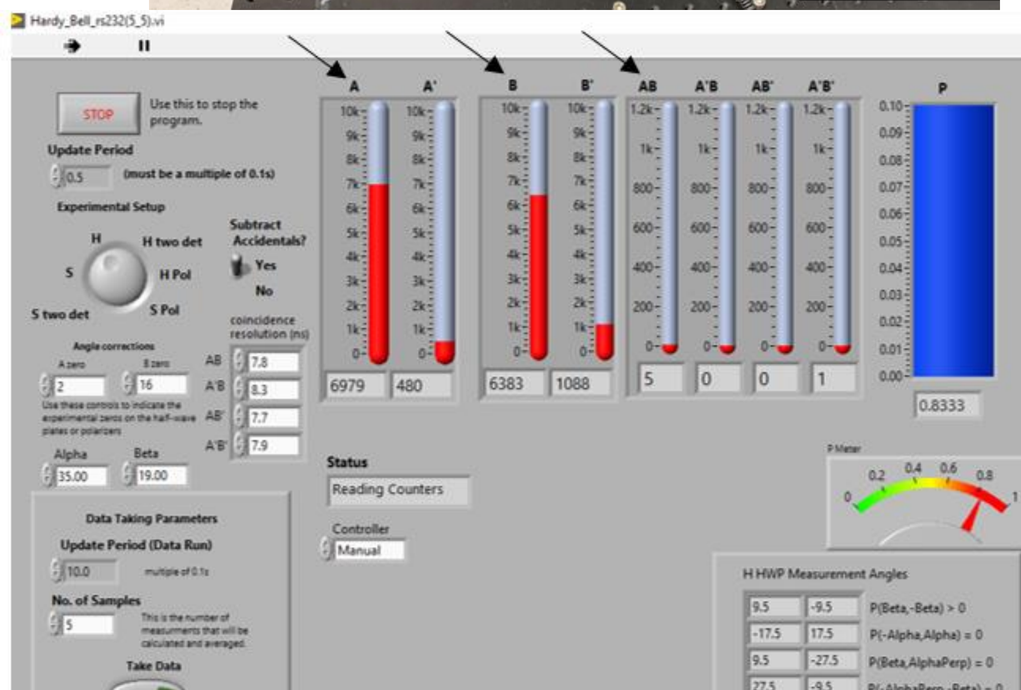
Quantum Entanglement Experimental Results





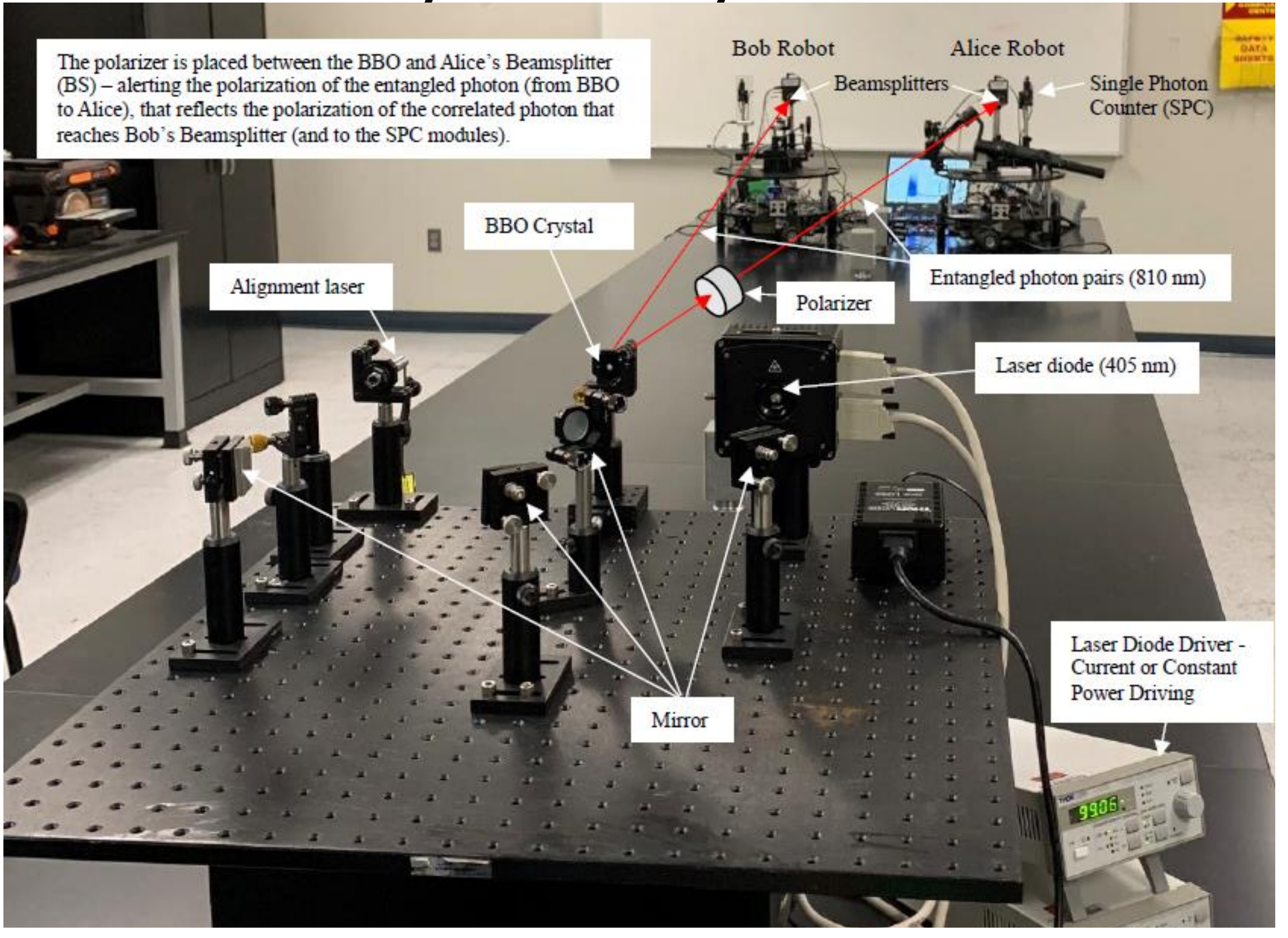
Alice (A, A'): $|H\rangle_A$ and $|V\rangle_A$

Bob (B, B'): $|H\rangle_B$ and $|V\rangle_B$

Coincidences AB, A'B, AB', A'B':

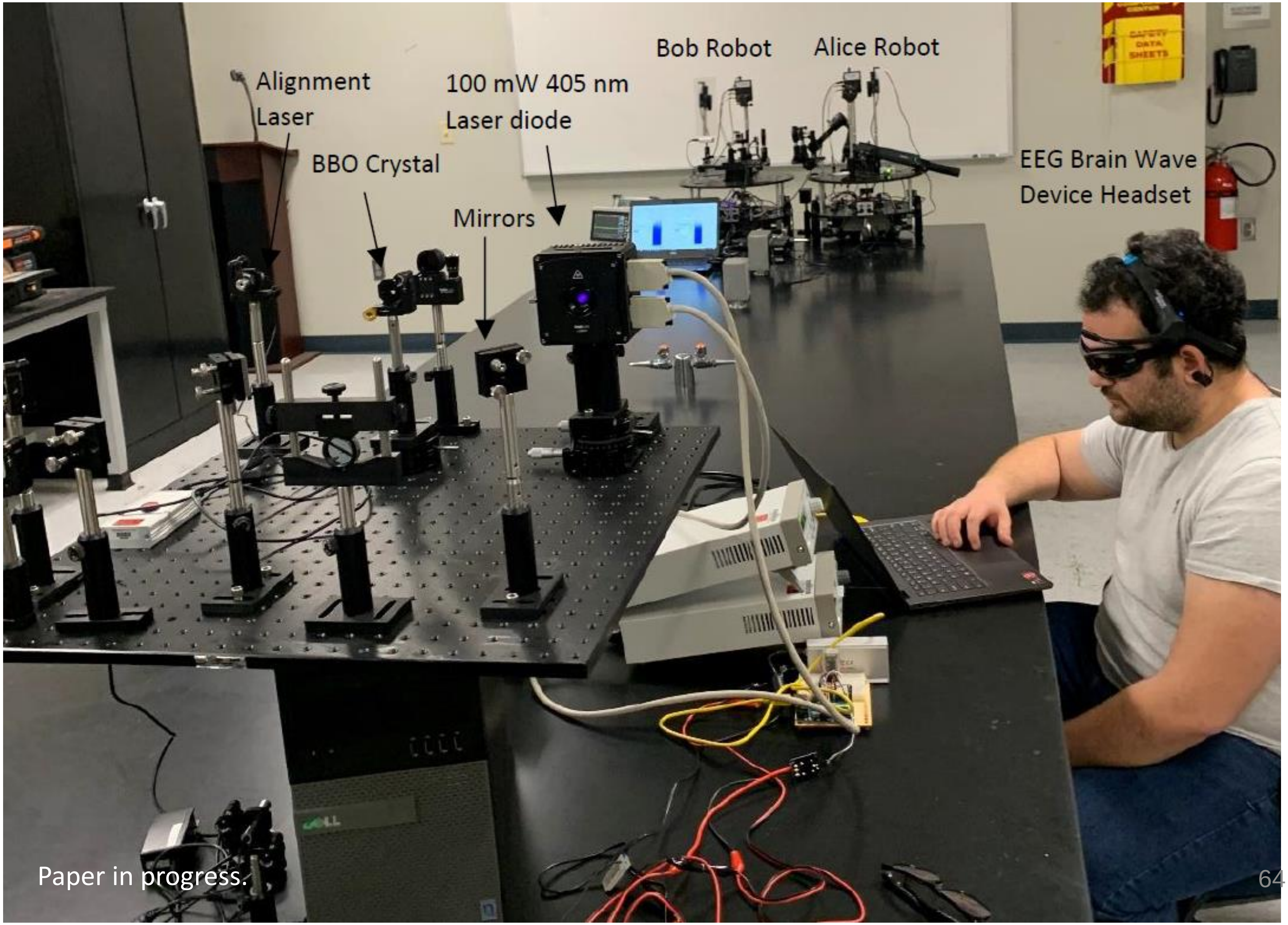
$$\frac{1}{\sqrt{2}}\left(|HV\rangle - |VH\rangle\right)$$

Quantum Teleportation for Control of Dynamic Systems and Autonomy



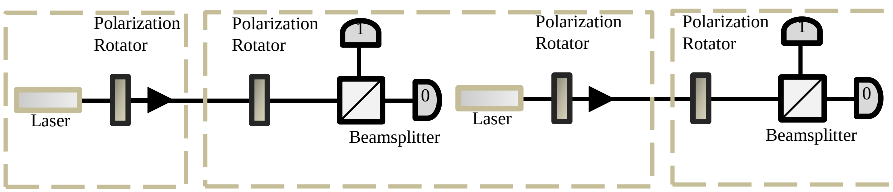
Farbod Khoshnoud, Lucas Lamata, Clarence W. De Silva, Marco B. Quadrelli, ***Quantum Teleportation for Control of Dynamic Systems and Autonomy***, *Mechatronic Systems and Control Journal*, 2020, in press [Preprint link].

Quantum Brain-Computer Interface (Q-BCI)



Paper in progress.

Quantum Cryptography for Cooperative Robotics and Autonomy



"Alice Robot" Eve "Bob Robot"

"Alice Robot" Eve "Bob Robot"

Alice HWP BASIS: + or ×	Bob HWP BASIS: + or ×	Result	BS	Digital results
$\|0^\circ\rangle$ (+)	$\|0^\circ\rangle$ (+)	$\|0^\circ\rangle$	Transmits the light	0
$\|90^\circ\rangle$ (+)	$\|0^\circ\rangle$ (+)	$\|90^\circ\rangle$	Reflects the light	1
$\|45^\circ\rangle$ (×)	$\|0^\circ\rangle$ (+)	Random $\|0^\circ\rangle$ and $\|90^\circ\rangle$	50% Reflects or transmit	No result
$\|-45^\circ\rangle$ (×)	$\|0^\circ\rangle$ (+)	Random $\|0^\circ\rangle$ and $\|90^\circ\rangle$	50% Reflects or transmit	No result
$\|0^\circ\rangle$ (+)	$\|45^\circ\rangle$ (×)	Random $\|0^\circ\rangle$ and $\|90^\circ\rangle$	50% Reflects or transmit	No result
$\|90^\circ\rangle$ (+)	$\|45^\circ\rangle$ (×)	Random $\|0^\circ\rangle$ and $\|90^\circ\rangle$	50% Reflects or transmit	No result
$\|45^\circ\rangle$ (×)	$\|45^\circ\rangle$ (×)	$\|90^\circ\rangle$	Reflects the light	1
$\|-45^\circ\rangle$ (×)	$\|45^\circ\rangle$ (×)	$\|0^\circ\rangle$	Transmits the light	0

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

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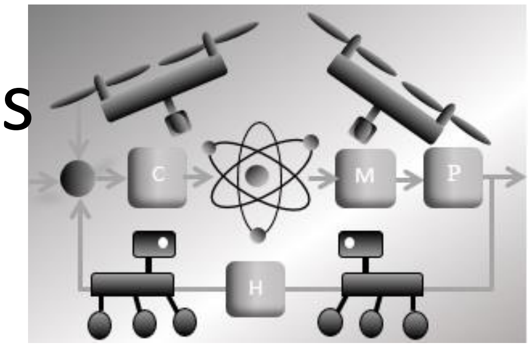
Theoretical Foundation of Quantum Multibody Dynamics

Quantum Mechanics

Schrödinger Equation

$$i\hbar \frac{d}{dt}|\psi(t)\rangle = \widehat{H}|\psi(t)\rangle$$



Classical Dynamics

Newton's Equations of Motion

$$\{\mathbf{F}\} = [\mathbf{M}]\{\mathbf{a}\}$$

The Feedback Control System?

$$TF = \frac{C(|\psi(t)\rangle)M(\{\mathbf{F}, |\psi(t)\rangle\})P(\{\mathbf{F}\})}{1 + C(|\psi(t)\rangle)M(\{\mathbf{F}\}, |\psi(t)\rangle)P(\{\mathbf{F}\})H}$$

F. Khoshnoud, I. I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamic Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF]

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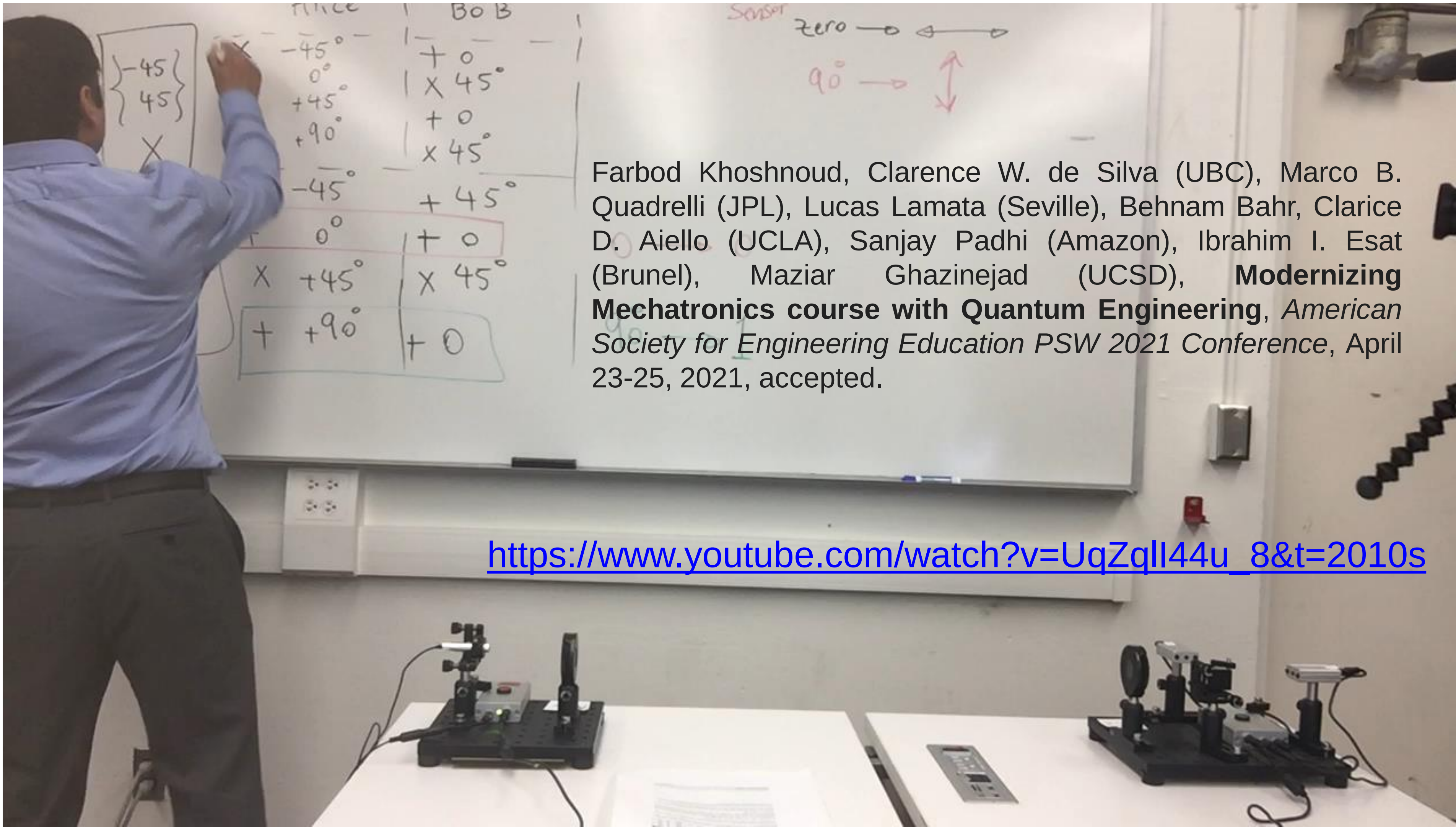
Modernizing Mechatronics with Quantum Engineering

Integrating Quantum Engineering into Mechatronics course, as well as traditional and cutting-edge Robotics and Autonomous Systems for the **Mechatronics course** for undergraduate and graduate courses



Farbod Khoshnoud, Clarence W. de Silva (UBC), Marco B. Quadrelli (JPL), Lucas Lamata (Seville), Behnam Bahr, Clarice D. Aiello (UCLA), Sanjay Padhi (Amazon), Ibrahim I. Esat (Brunel), Maziar Ghazinejad (UCSD), **Modernizing Mechatronics course with Quantum Engineering**, *American Society for Engineering Education PSW 2021 Conference*, April 23-25, 2021, accepted.

https://www.youtube.com/watch?v=UqZqlI44u_8&t=2010s

Working with **Chief Dario Robinson** to **apply Quantum Robotics** opportunities for **Security and Emergency Response** with unmatched **guaranteed safety from interception, and true security** using applied Quantum technologies.

“Pushing the boundaries of the engineering **beyond existing techniques**.”

- Self-powered Dynamic Systems
- Nature/Bio-inspired Dynamic Systems
- Quantum Multibody Dynamics, Robotics, and Autonomy
- Optimal Uncertainty Quantification for engineering Systems

Optimal Uncertainty Quantification for engineering systems

Probability of function $G(X)$ to be greater than b (i.e. to fail) is less than ϵ:

$$\mathbb{P}[G(X) \geq b] \leq \epsilon$$

$(G,\ \mathbb{P}\ ) \in \mathcal{A}$, and the admissible extremal scenarios $\mathcal{A}$ is:

$$\mathcal{A} \subset \left\{(g,\mu) \middle| \begin{matrix} g\colon \mathcal{X} \to \mathbb{R} \\ \mu \in \mathcal{P}(\mathcal{X}) \end{matrix} \right\}$$

$$\mathcal{A} := \left\{(g,\mu) \middle| \begin{matrix} g\colon \mathcal{X}_1 \times \cdots \times \mathcal{X}_m \to \mathbb{R} \\ \mu = \mu_1 \otimes \mu_2 \otimes \cdots \otimes \mu_m \\ m_1 \leq \mathbb{E}_\mu\,[g] \leq m_2 \end{matrix} \right\}$$

The optimal bounds on the probability of the system:

$$\mathcal{L}(\mathcal{A}) := inf_{(f,\mu)\in\mathcal{A}}\ \mu[g(X) \geq b]$$

$$\mathcal{U}(\mathcal{A}) := sup_{(f,\mu)\in\mathcal{A}}\ \mu[g(X) \geq b]$$

$$\mathcal{L}(\mathcal{A}) \leq \mathbb{P}[G(X) \geq b] \leq \mathcal{U}(\mathcal{A})$$

Solve the constrained optimization problem over $\mathcal{U}(\mathcal{A})$:

$$\mathcal{U}(\mathcal{A}) := \sup_{(G,\mu)\in\mathcal{A}} \mu[G(X) \leq 0]$$

Example:

$$\mathcal{A} := \left\{(g,\mu) \middle| \begin{matrix} g\colon \mathcal{X}_1 \times \mathcal{X}_2 \times \mathcal{X}_3 \to \mathbb{R} \\ \mu = \mu_1 \otimes \mu_2 \otimes \mu_3 \\ \boldsymbol{r}_{j\_min} \leq \mathbb{E}_\mu\,[\boldsymbol{r}_j] \leq \boldsymbol{r}_{j\_max} \\ g = \boldsymbol{r}_j \end{matrix} \right\}$$

$$\mathcal{U}(\mathcal{A}) := \sup_{(\boldsymbol{r},\mu)\in\mathcal{A}} \mu[\boldsymbol{r}_i(X) \leq 0]$$

Houman Owhadi, C. Scovel, T. Sullivan, M. McKerns and M. Ortiz, "**Optimal Uncertainty Quantification**," SIAM Review, 2012.

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Achieving Excellence by collaborating with the leaders

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MINISTRY OF DEFENCE

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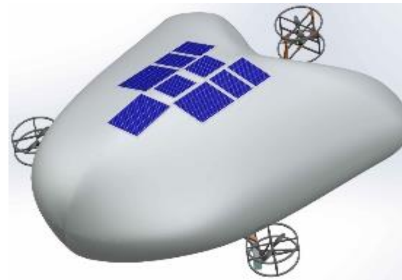
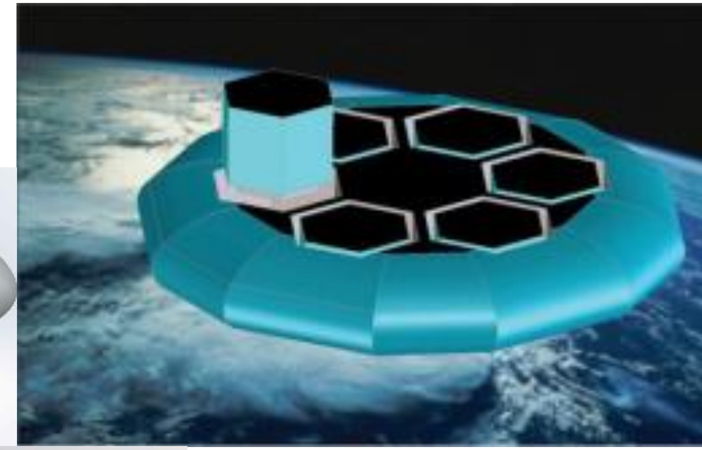
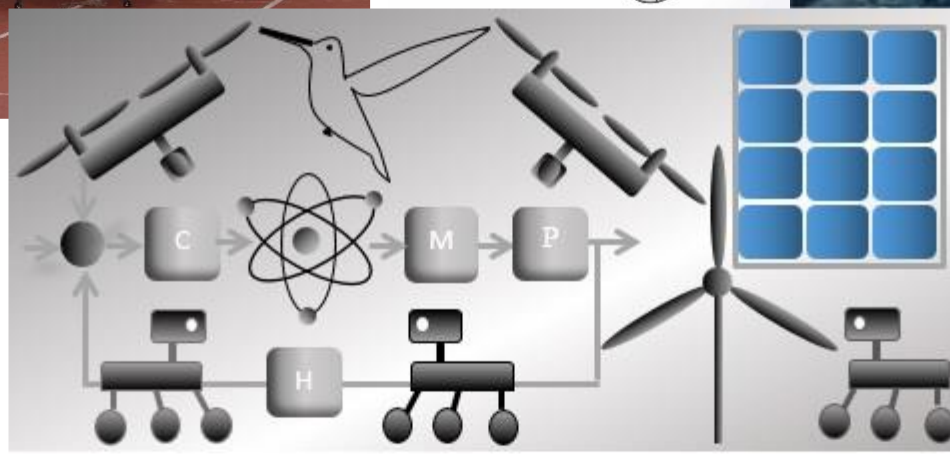
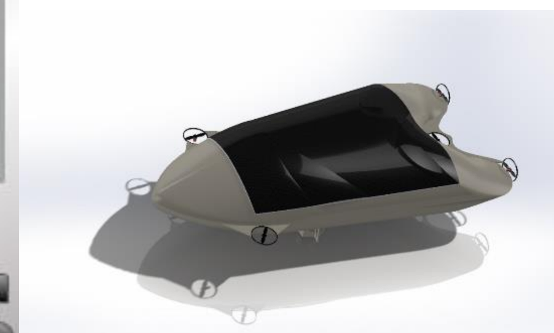
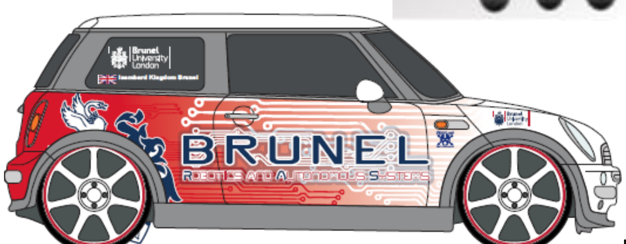
Thank you!

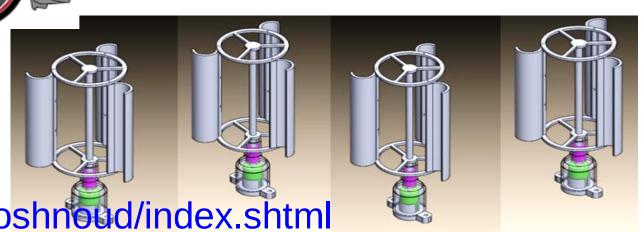


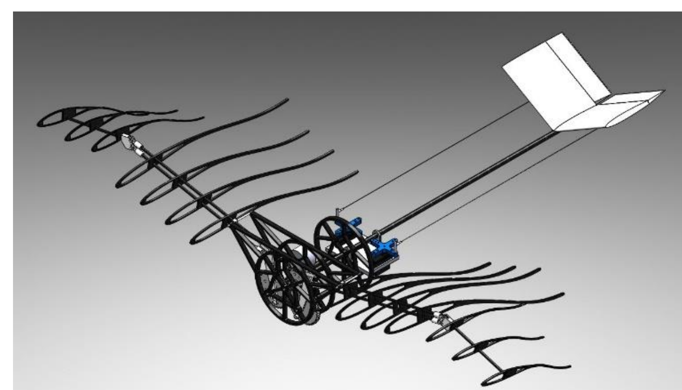












https://www.cpp.edu/faculty/fkhoshnoud/index.shtml