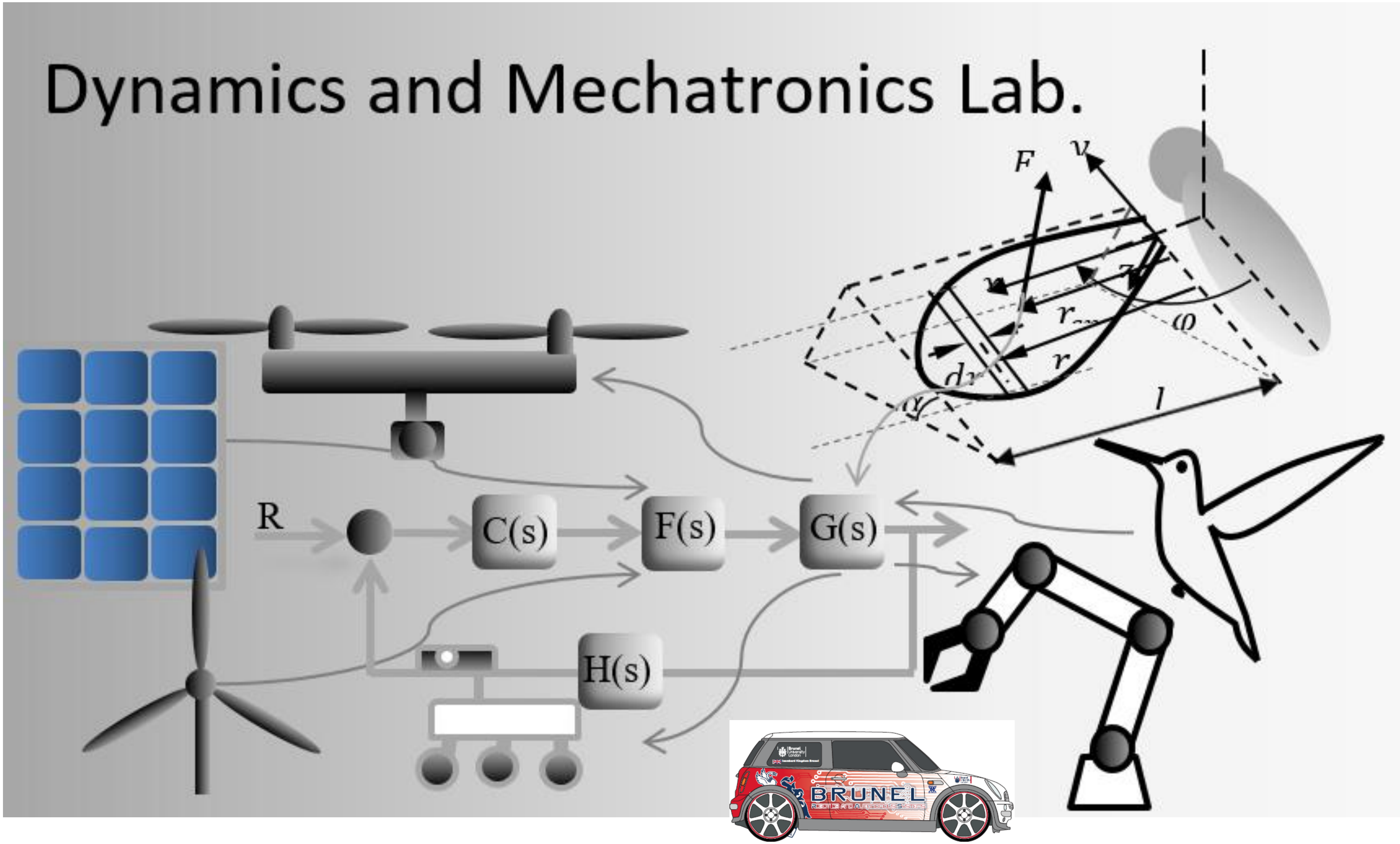

Dr. Farbod Khoshnoud
Electromechanical Engineering Technology, California State Polytechnic University, Pomona, CA, fkhoshnoud@cpp.edu
https://www.cpp.edu/faculty/fkhoshnoud/index.shtml

Greatest Engineering Achievements OF THE 20TH CENTURY

• About • Timeline

Welcome!

How many of the 20th century's greatest engineering achievements will you use today? A car? Computer? Telephone? Explore our list of the top 20 achievements and learn how engineering shaped a century and changed the world.

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

Greatest Achievements

Source: http://www.engineeringchallenges.org/

14 Grand Challenges for Engineering in the 21st Century

- Grand Challenges Report
- Advance Personalized Learning
- Make Solar Energy Economical
- Enhance Virtual Reality
- Reverse-Engineer the Brain
- Engineer Better Medicines
- Advance Health Informatics
- Restore and Improve Urban Infrastructure
- Secure Cyberspace
- Provide Access to Clean Water
- Provide Energy from Fusion
- Prevent Nuclear Terror
- Manage the Nitrogen Cycle
- Develop Carbon Sequestration Methods
- Engineer the Tools of Scientific Discovery

Source: http://www.engineeringchallenges.org/

14 Grand Challenges for Engineering in the 21st Century

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- Engineer the Tools of Scientific Discovery

Source: http://www.engineeringchallenges.org/

Engineer the Tools of Scientific Discovery

Engineer the Tools of Scientific Discovery

- **How will engineering impact research**

Engineers will continue to be partners with scientists in the great quest for **understanding many unanswered questions of nature**.

Interdisciplinary Multidisciplinary research.

- **How will engineering help us explore the universe**

The underlying question is whether there exists, as Einstein believed, one single, ultimate **underlying law that encompasses all physics** in a **unified mathematical framework**.

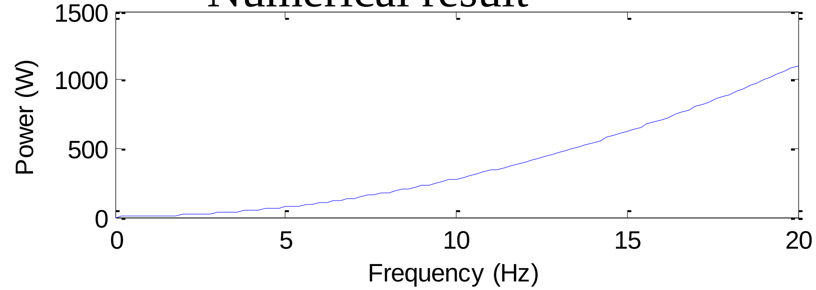
Another possible avenue to discovering a unified law might be by achieving a deeper understanding of how the **world's tiniest and most basic building blocks work, the foundations of quantum physics**.

All things considered, the frontiers of nature represent the grandest of challenges, for engineers, scientists, and society itself. **Engineering's success in finding answers to nature's mysteries** will not only advance the understanding of life and the cosmos, but also provide engineers with fantastic new prospects to apply in enterprises that **enhance the joy of living and the vitality of human civilization**.

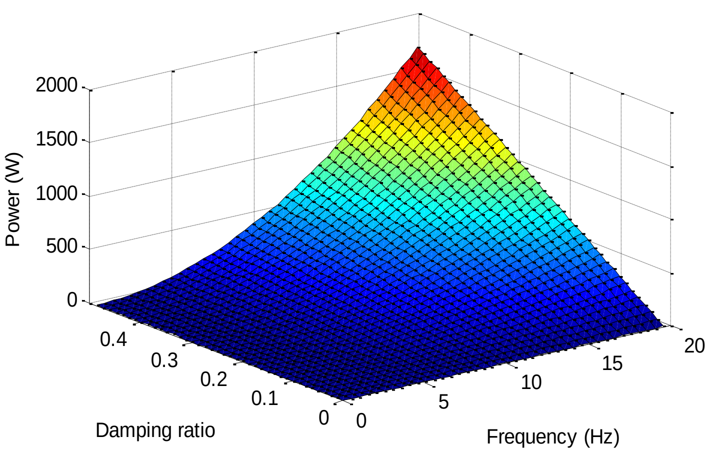
Source: http://www.engineeringchallenges.org/

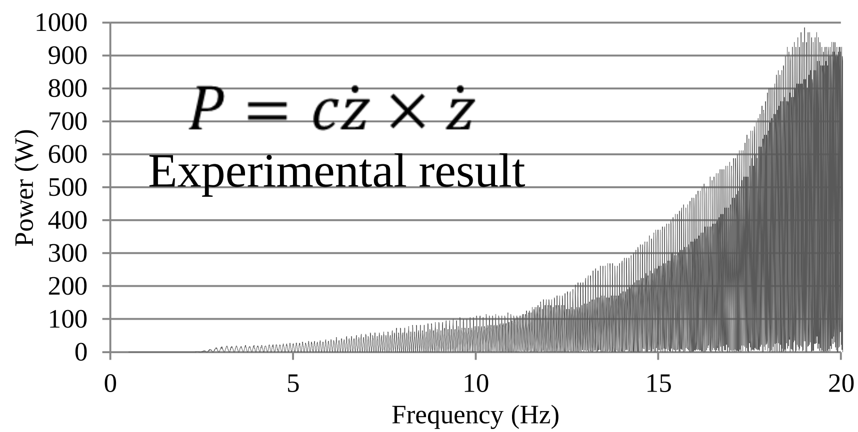
Vibration Control - Energy Harvesting – Regenerative Shock Absorbers

Numerical result



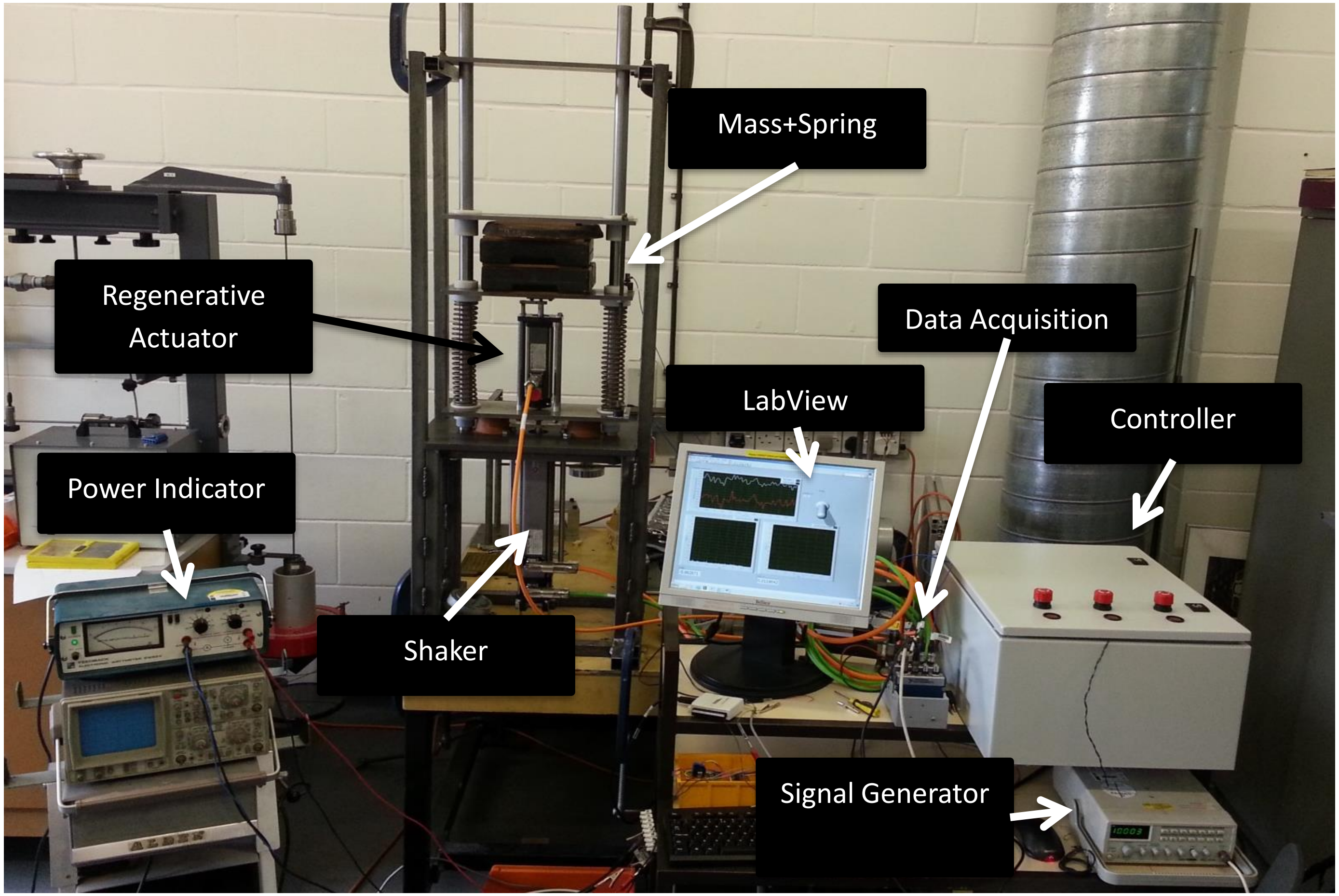
$$P = \frac{m\omega^3 Y Z_{max} \zeta . \eta}{\sqrt{(1-\eta^2)^2 + (2\zeta\eta)^2}}$$





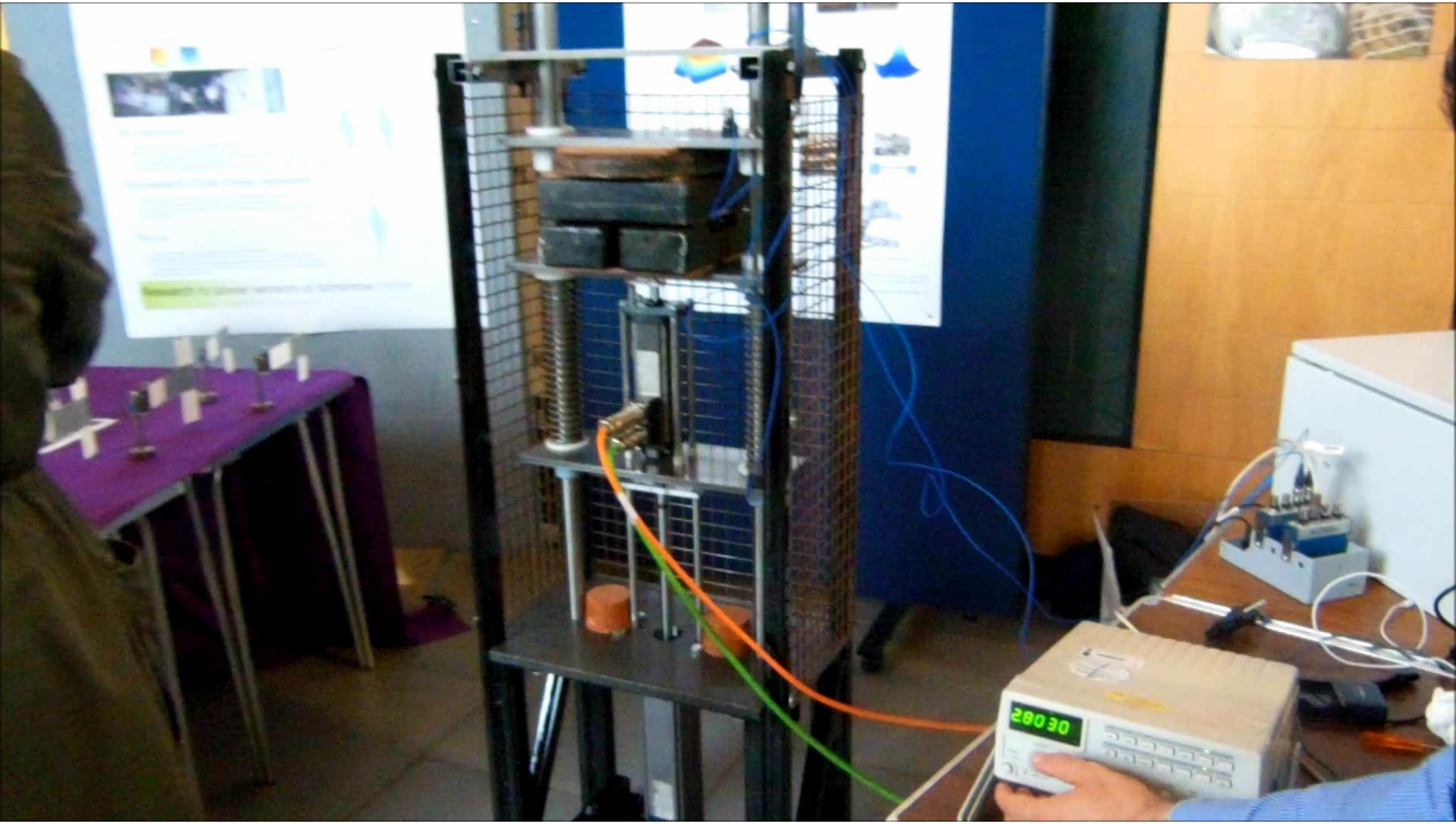
Farbod Khoshnoud, Dinesh B. Sundar, Nuri M. Badi, Yong K. Chen, Rajnish K. Calay and Clarence W. de Silva, **Energy harvesting from suspension system using regenerative force actuators**, International Journal of Vehicle Noise and Vibration *Vol. 9, Nos. 3/4, pp. 294 - 311, 2013.*

Energy harvesting for vibration control



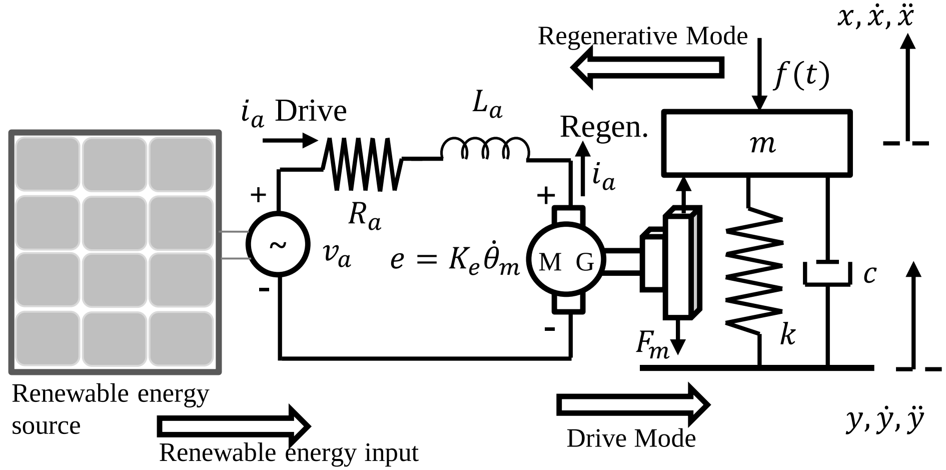
Farbod Khoshnoud, Y. Zhang, R. Shimura, A. Shahba, G. Jin, G. Pissanidis, Y.K. Chen, Clarence W. De Silva, **Energy regeneration from suspension dynamic modes and self-powered actuation**, *IEEE/ASME transaction on Mechatronics*, Volume: 20, Issue: 5, pp. 2513 - 2524, 2015.

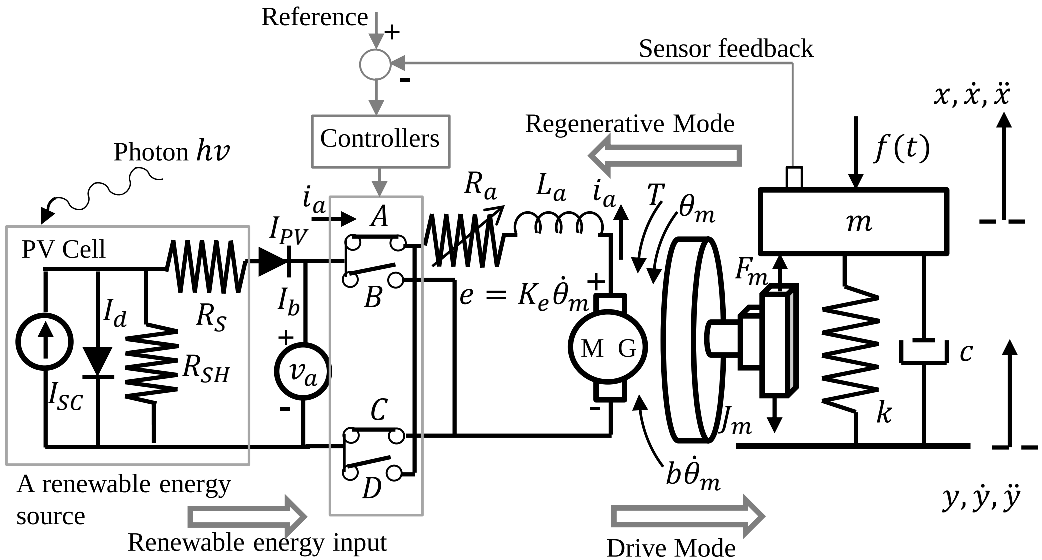
The experimental energy harvesting rig



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]

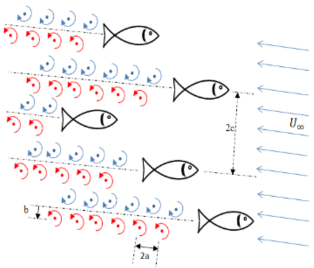
Development of Self-powered Dynamic Systems



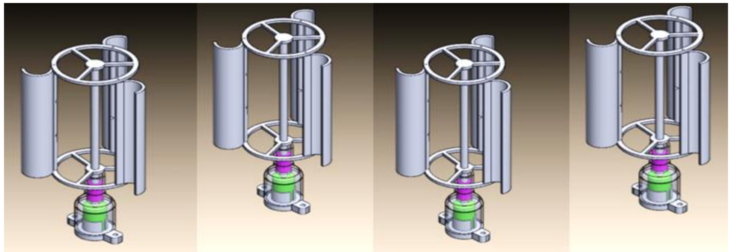


Farbod Khoshnoud, M. M. McKerns, Clarence W. De Silva, Ibrahim Esat, Houman Owhadi, **Self-powered Dynamic Systems in the framework of Optimal Uncertainty Quantification**, Journal of Dynamic Systems, Measurement, and Control, Volume 139, Issue 9, 2017.

Mechatronics

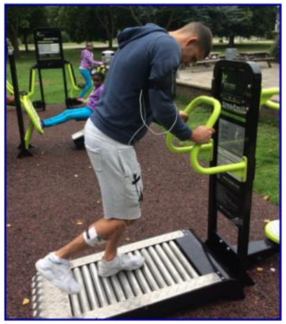


Solar aircraft

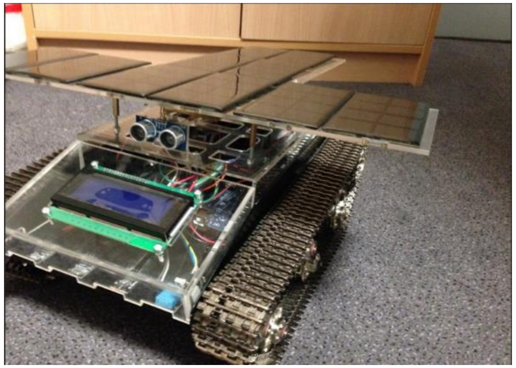


Bio-inspired vertical axis wind turbines

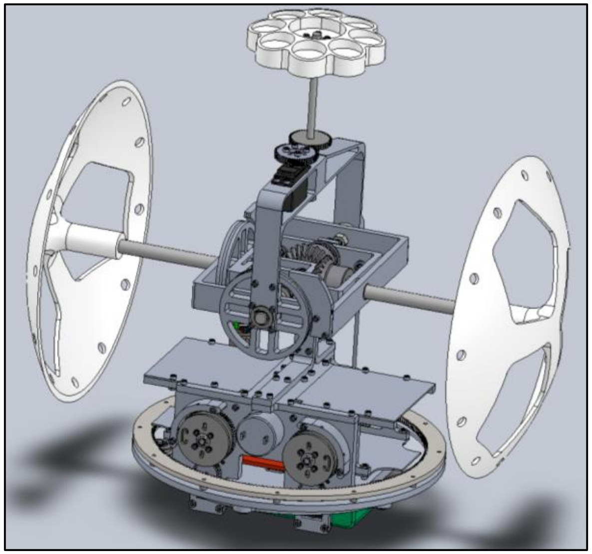
Energy from human motion



Energy harvesting from human motion

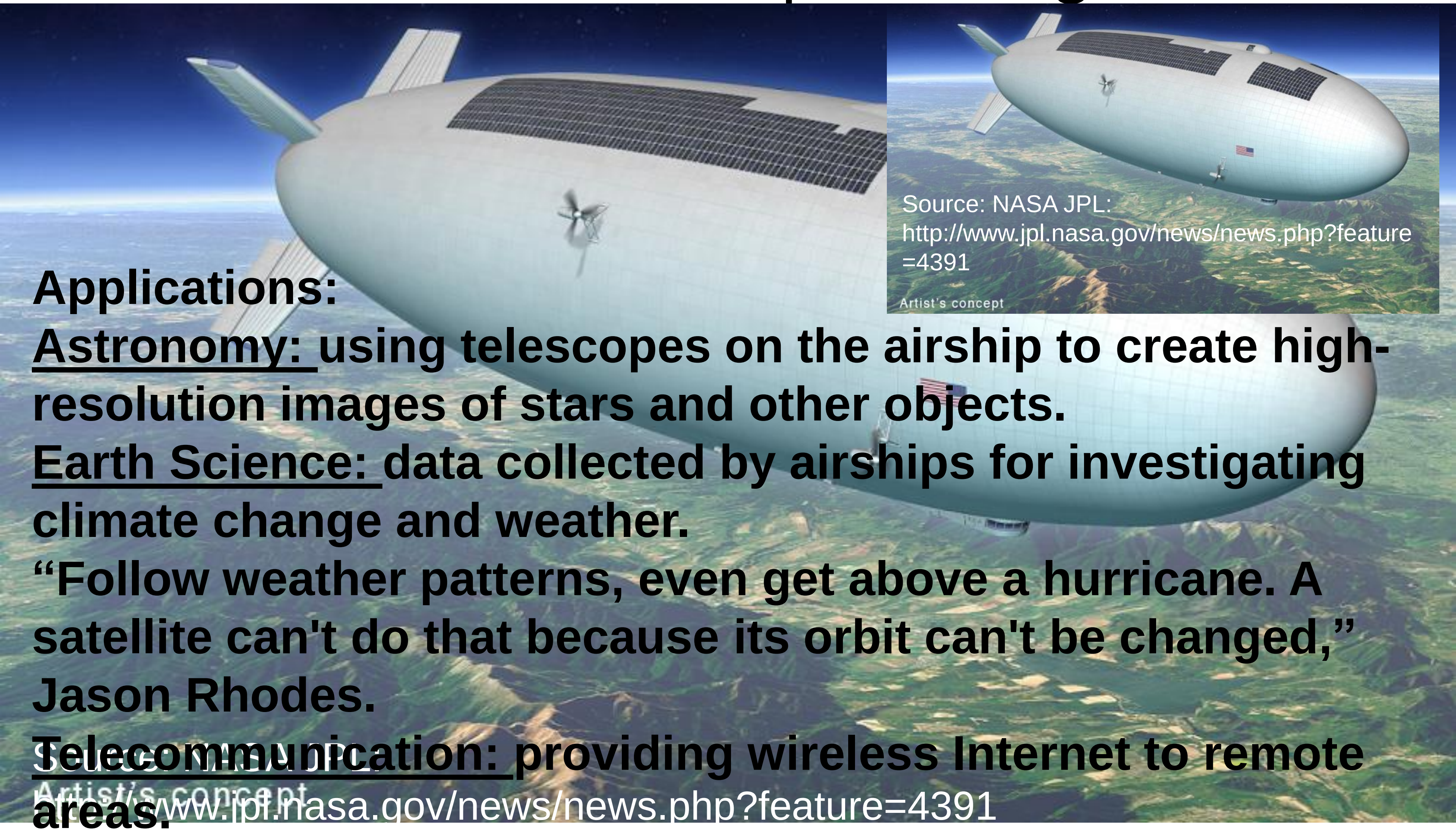


Autonomous vehicles



BB-8 Droid
Mechatronics Club

NASA Jet Propulsion Laboratory
20-20-20 Airship Challenge



Applications:

<u>Astronomy:</u> using telescopes on the airship to create high-resolution images of stars and other objects.

<u>Earth Science:</u> data collected by airships for investigating climate change and weather.

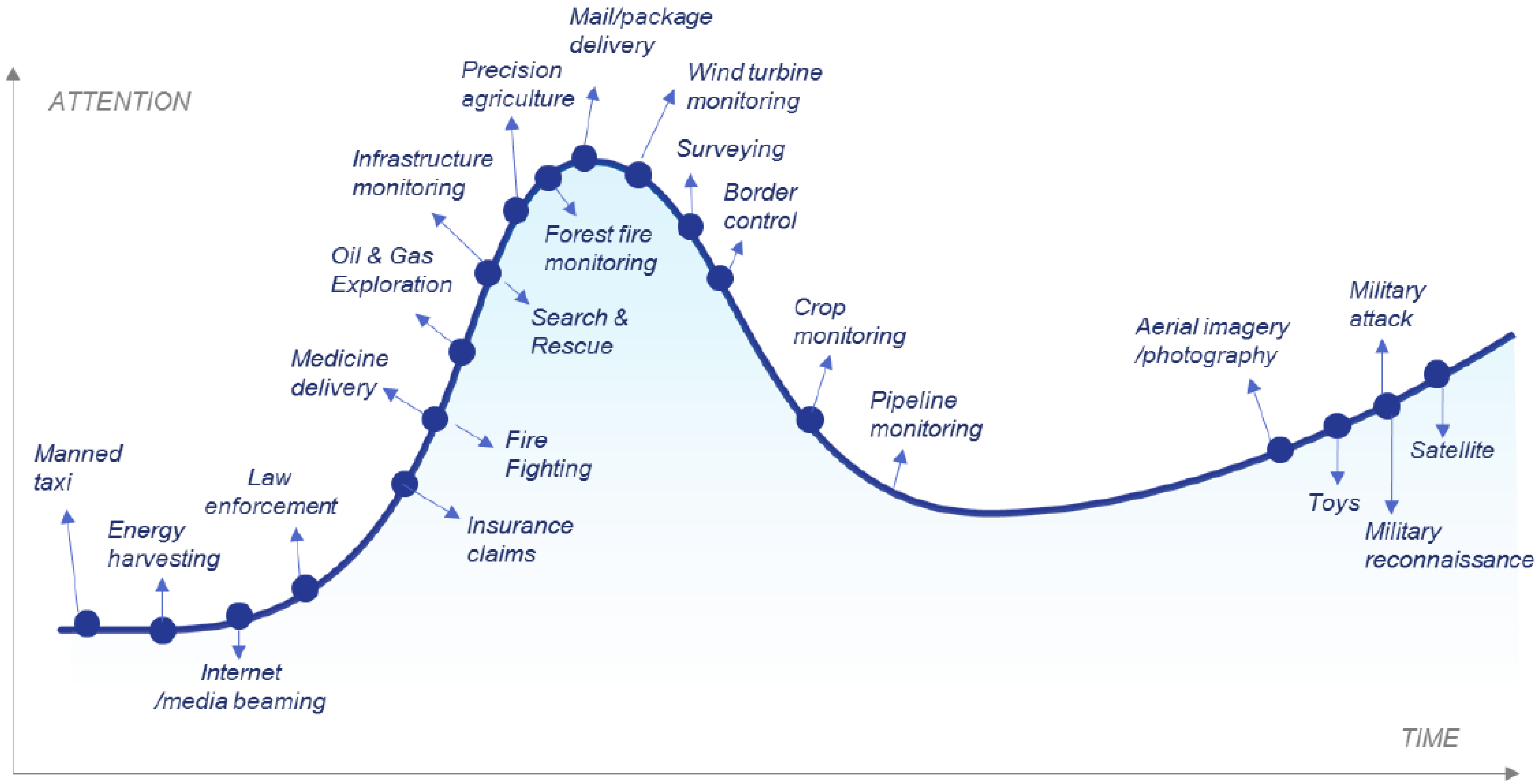
"Follow weather patterns, even get above a hurricane. A satellite can't do that because its orbit can't be changed," Jason Rhodes.

<u>Telecommunication:</u> providing wireless Internet to remote areas.

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

Ref.: Farbod Khoshnoud, Clarence de Silva, Jason D Rhodes, Alina Kiessling, Marco Quadrelli, et al., Solar Powered Autonomous Aerial Vehicles: Towards infinite endurance UAVs.

Autonomous Vehicles



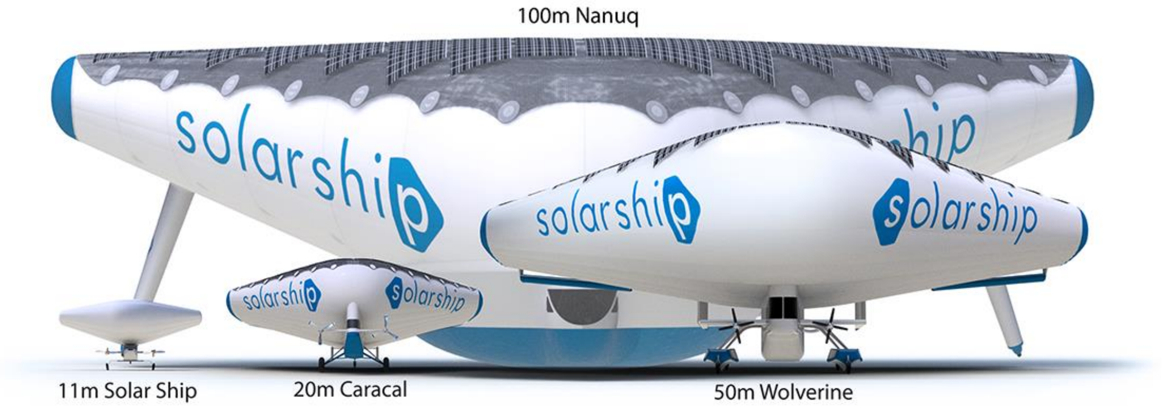
IDTechEx report on [‘Electric UAV Drones: Autonomous Energy Independent 2017-2027’]

State-of-the-Art

Lockheed Martin Hybrid Airship

Airlander 10


Aerostat



Drones: from energy harvesting to energy independence

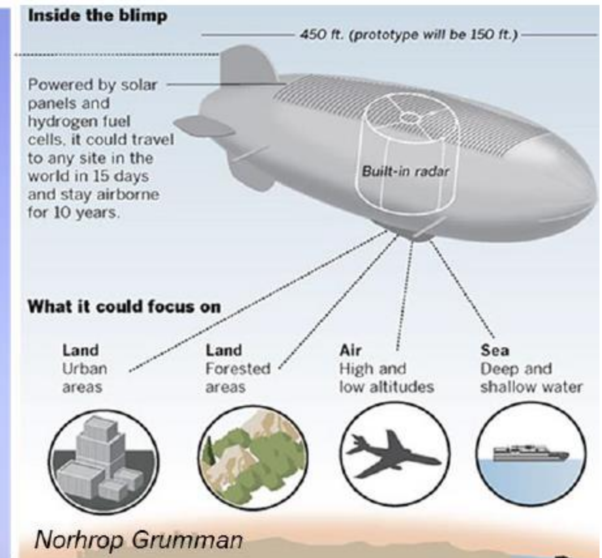
Dirisolar


Lockheed Martin


Turtle airship


Brunel Solar Powered Robotic Airship 2016


China Aerospace



Norhrop Grumman

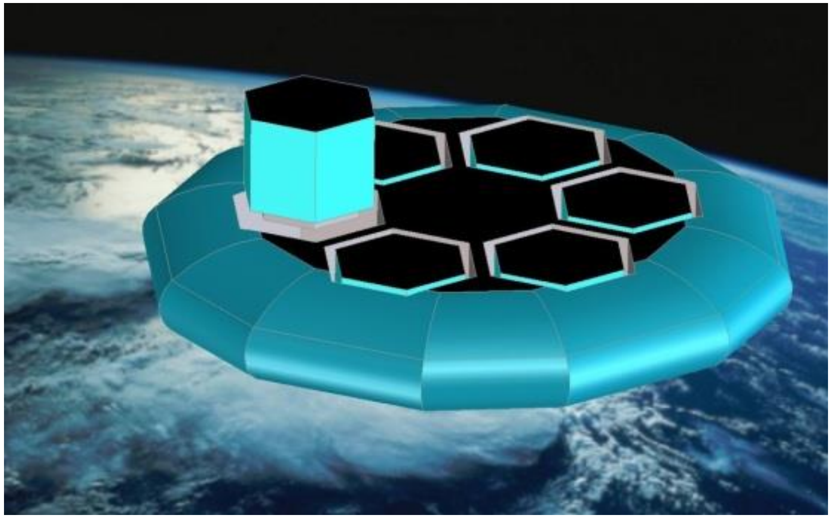
- Energy independence is the endgame of electric vehicles?

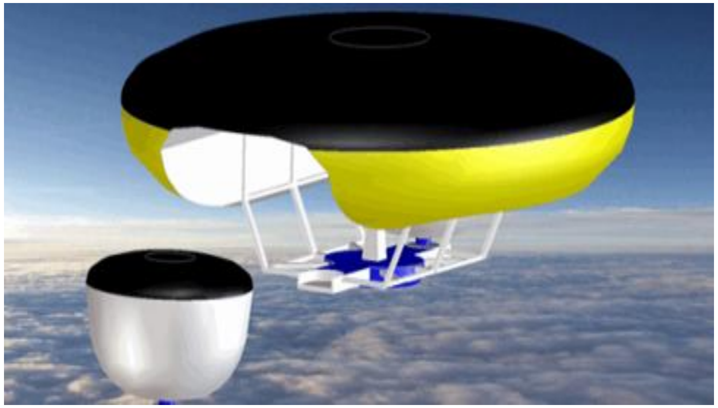
IDTechEx report on *'Energy Independent Electric Vehicles Land, Water, Air 2017: 2037'*

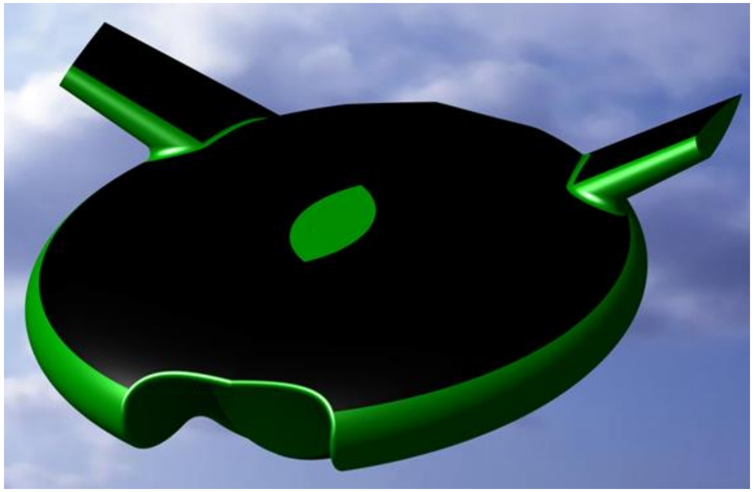
Solar Powered UAVs (3 million euros)

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





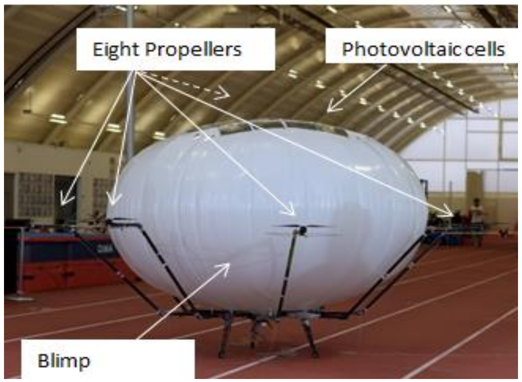


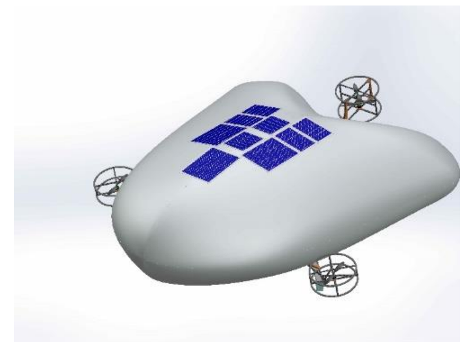
Reference:
Farbod Khoshnoud, Y.K. Chen, and R.K. Calay, **On Power and Control Systems of Multibody Advanced Airship for Transport,** *International journal of Modelling, Identification and Control, Int. J. Modelling, Identification and Control, Vol. 18, No. 4, 2013.*

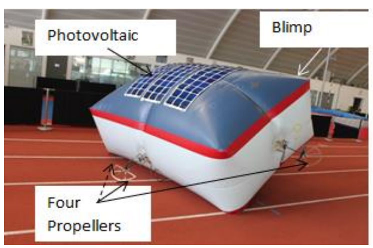
Self-Powered Solar Autonomous Aerial Vehicles

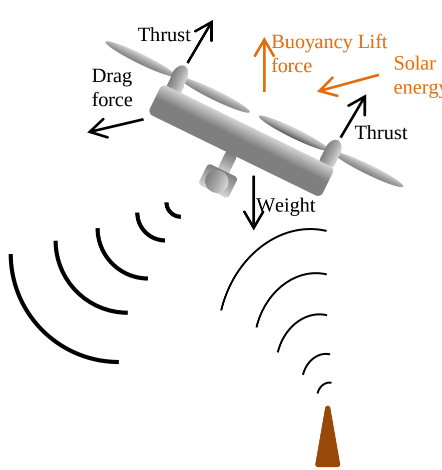
Project Summary
Building a self-sustained solar powered aerial vehicle towards "infinite" endurance operation as a self-powered system.

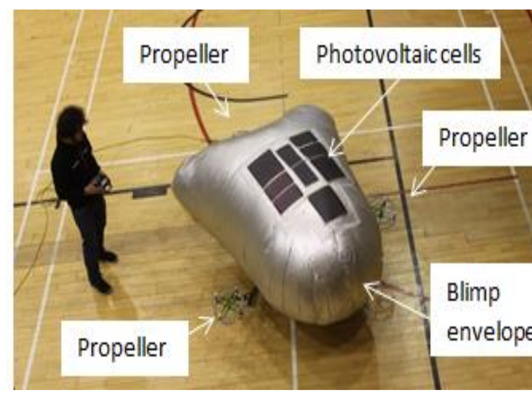
Benefits and applications: no limit
Delivery, Traffic control, Agricultural, Surveillance, Search and rescue, Security, Telehealth, Beaming internet, Aerial robotics, Maintenance…







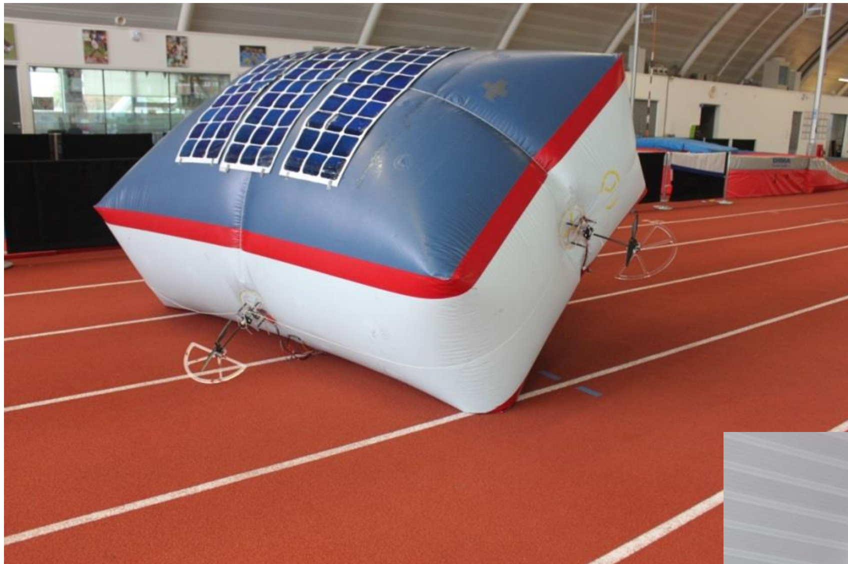


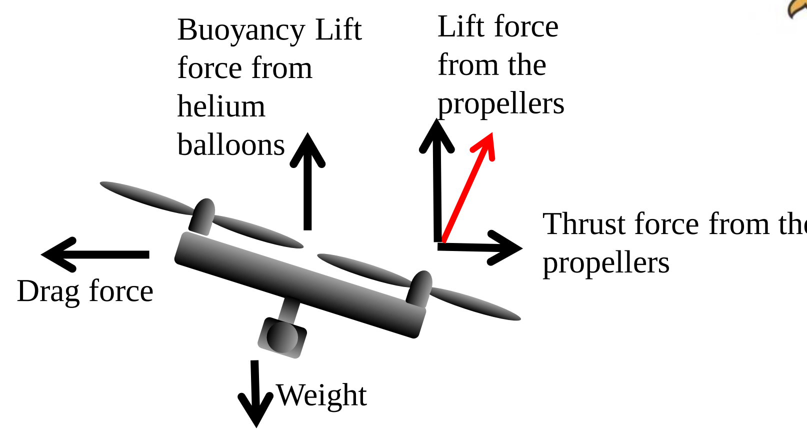


Ref: Farbod Khoshnoud, Michael McKerns, Clarence W. De Silva, Ibrahim Esat, Richard H.C. Bonser, Houman Owhadi, **Self-powered and Bio-inspired Dynamic Systems: Research and Education,** *ASME 2016 International Mechanical Engineering Congress and Exposition*, Phoenix, Arizona, USA, 2016.

Ref.: Farbod Khoshnoud, Clarence de Silva, Jason D Rhodes, Alina Kiessling, Marco Quadrelli, et al., Solar Powered Autonomous Aerial Vehicles: Towards infinite endurance UAVs.

Quadrotor solar powered UAVs





Brunel Solar-powered airship: Towards infinite endurance UAVs

- Neutral/partial buoyancy for lift
- Photovoltaics cells for recharging 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.

Quadrotor solar powered UAV

[Video Link] 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.

Octorotor solar powered UVs

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

Farbod Khoshnoud, et al., **Self-powered Solar Aerial Vehicles: towards infinite endurance UAVs**, in progress.

Video Link

Brunel UVs

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

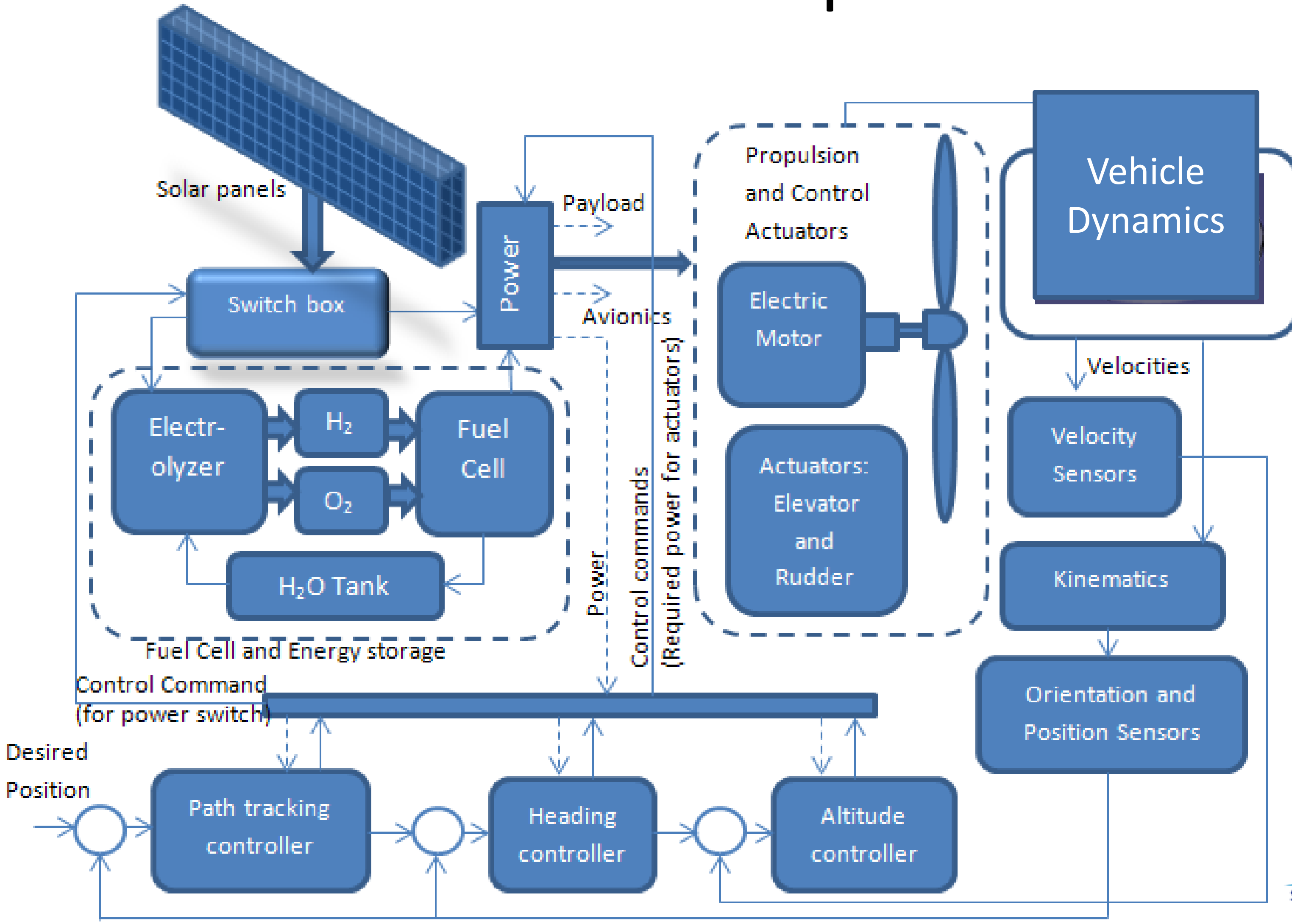
Students: Oliver Salsbury, Daniel Raineri, Giuliano Morreale, Timothy Taylor, Daniel Sutch, Psam Elyon

Farbod Khoshnoud, et al., **Self-powered Solar Aerial Vehicles: towards infinite endurance UAVs**, in progress. Video Link

Brunel UVs

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

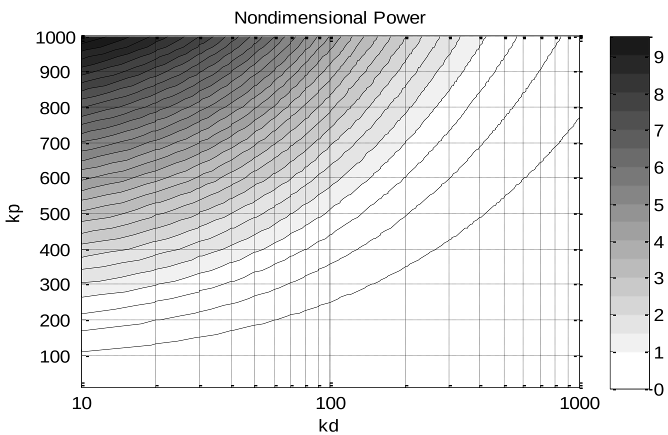
Autonomous solar-fuel cell powered vehicles



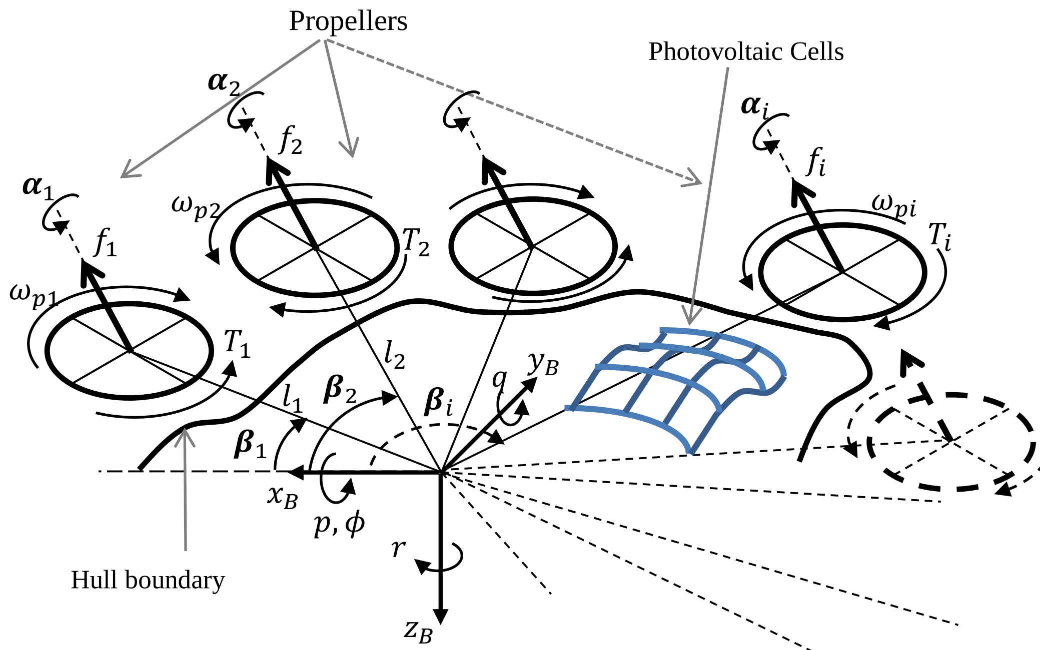
SEVENTH FRAMEWORK PROGRAMME

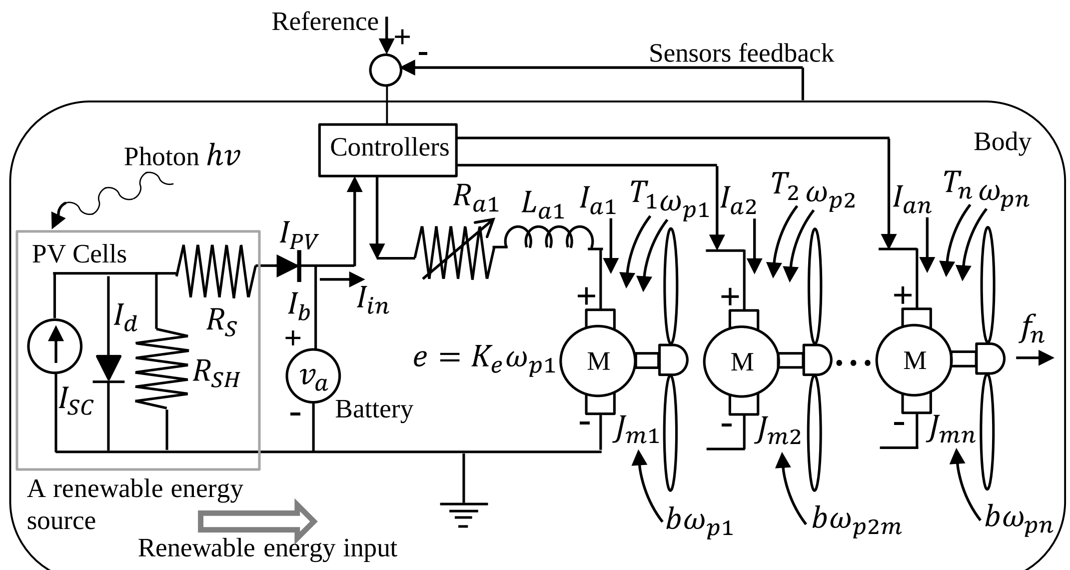
Farbod Khoshnoud, Clarence W. De Silva, et al., **Mechatronics: Fundamentals and Applications**, Taylor & Francis / CRC Press, 2015.

Self-powered Vehicles: Towards Infinite Endurance UVs



Farbod Khoshnoud, *Fresno State*
Ibrahim I. Esat, George Glass, Oliver Salsbury, *Brunel University London*
Clarence W. de Silva
University of British Columbia
Jason D. Rhodes, Alina A. Kiessling, Marco B. Quadrelli
Jet Propulsion Laboratory, NASA

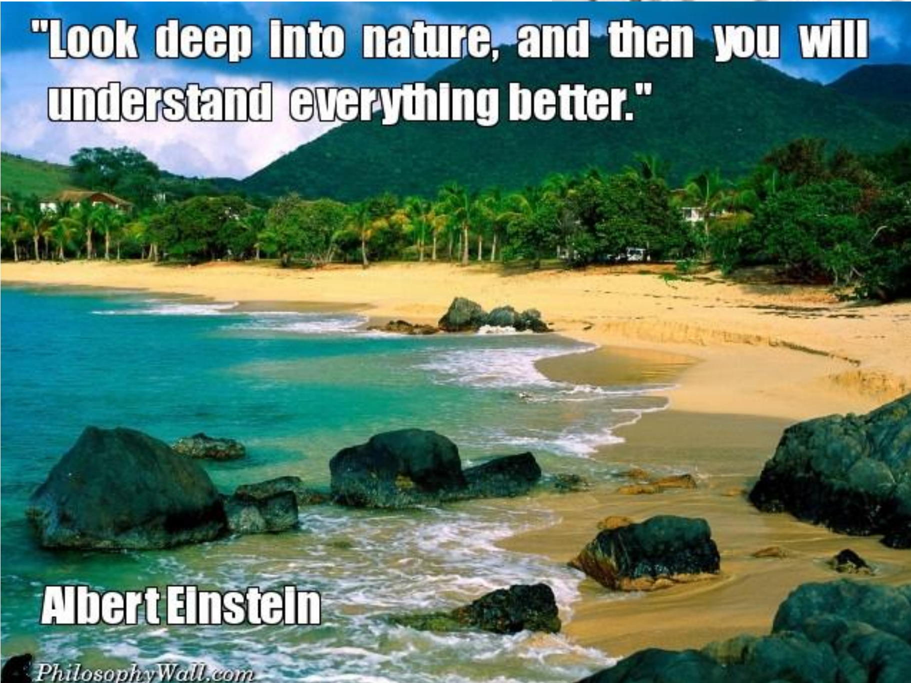


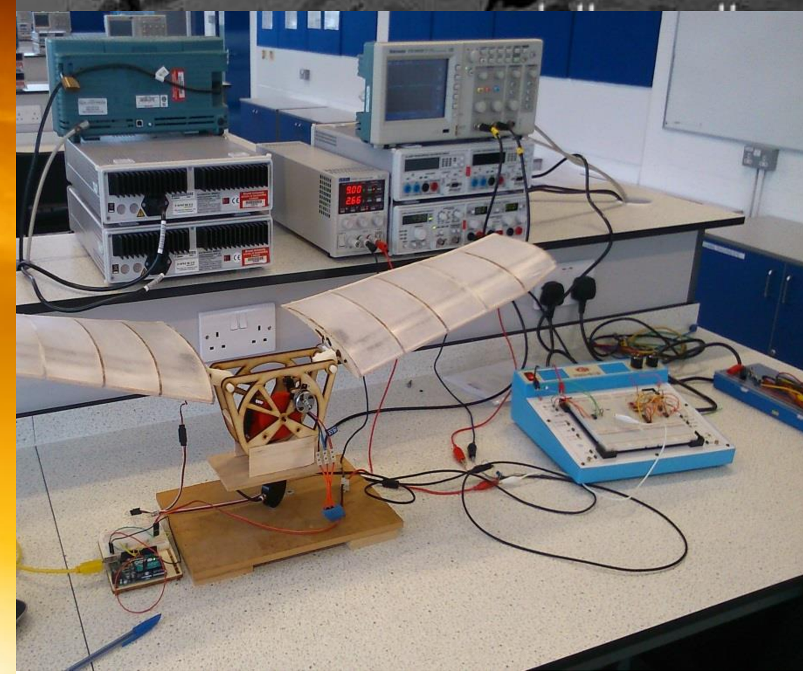


Research-Informed Service-Learning

Autonomous traffic monitoring, and situation awareness

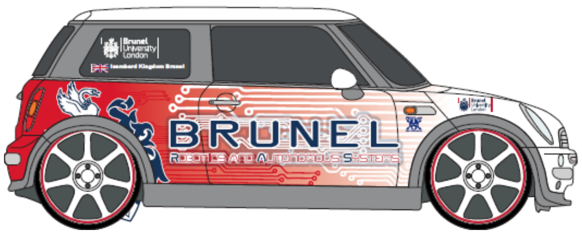
Ref: Farbod Khoshnoud, Dario Robinson, Clarence W. de Silva, Ibrahim I. Esat, Richard H.C. Bonser, Marco B. Quadrelli, **Research-informed service-learning in Mechatronics and Dynamic Systems**, ASEE PSW 2019 Conference April 4-6, 2019, Los Angeles, CA.

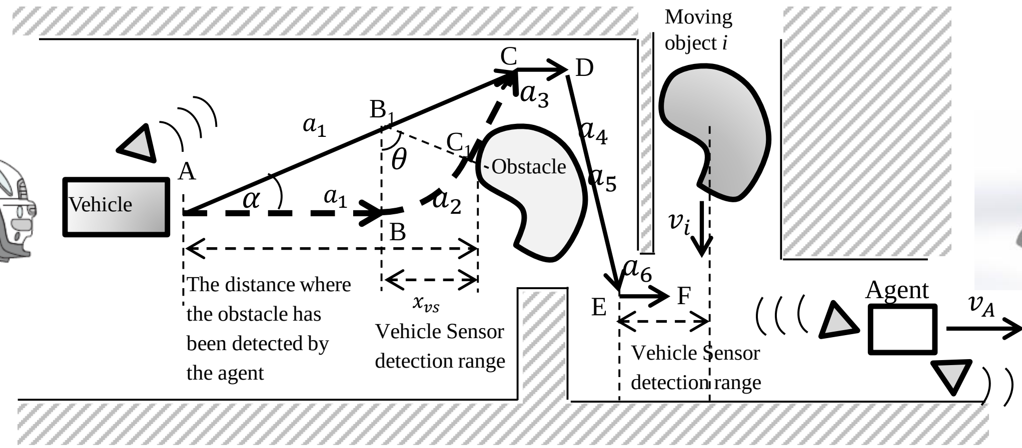

"Look deep into nature, and then you will understand everything better."
Albert Einstein
PhilosophyWall.com

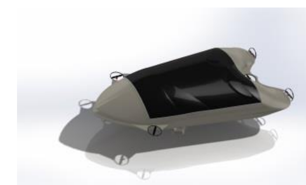


Self-Driving Cars projects

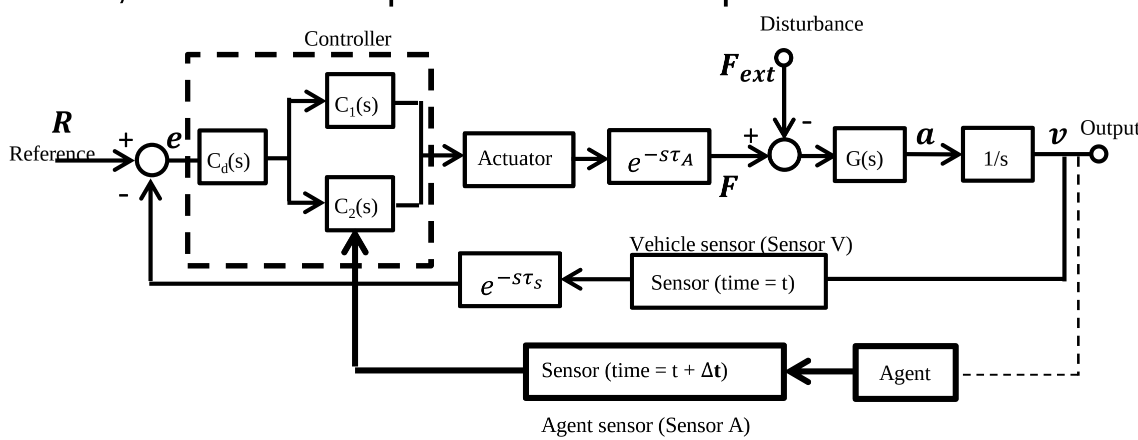
Bioinspired Psi Intelligent Control for Autonomous Systems.







“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

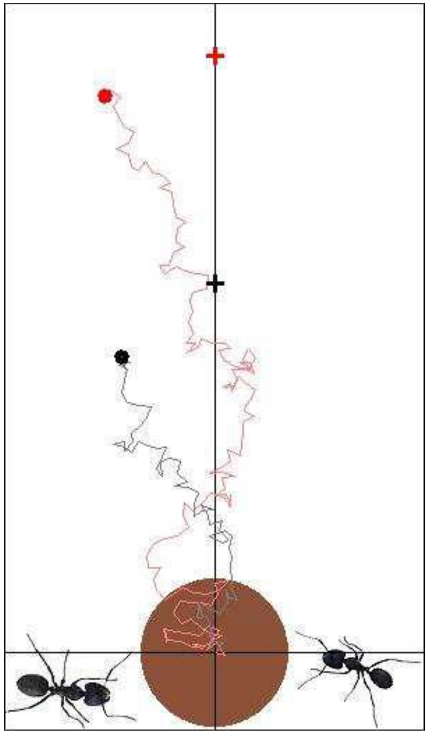


Figure: Typical stochastic paths of the pebble as pushed by quantum entangled ants (red) as well as by independent ants (black).

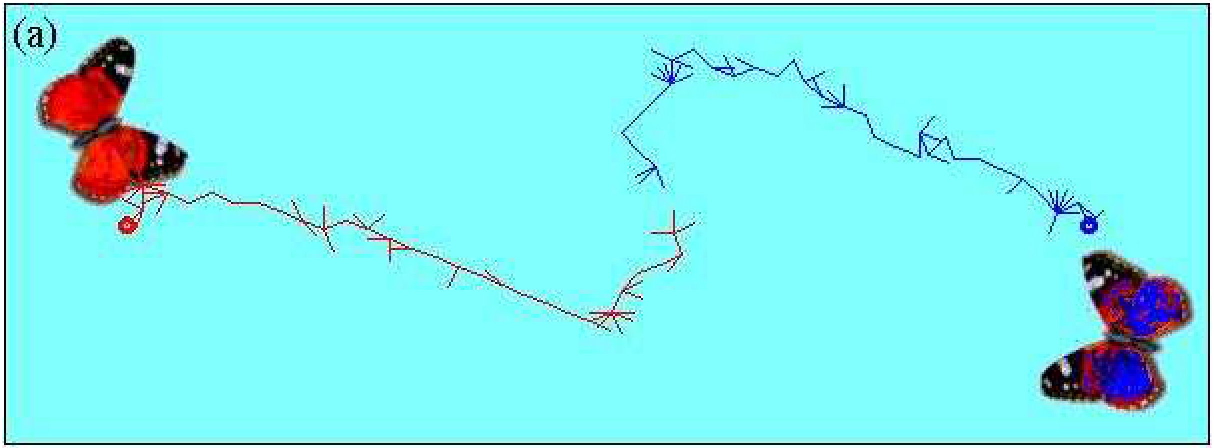


Figure: (a): Typical flight paths of the two butterflies.
(b): The quantum entangled butterflies needed an average of 2778 short flights to find each other, versus 5255 short flights for the independent butterflies.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security

Singlet state

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

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

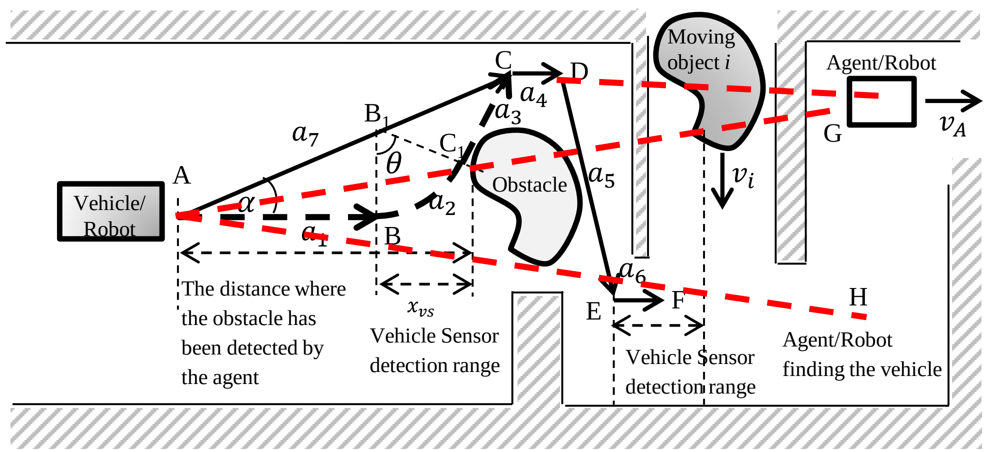
$$p_{\uparrow\downarrow}^{(s)} = p_{\downarrow\uparrow}^{(s)} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

Triplet state

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

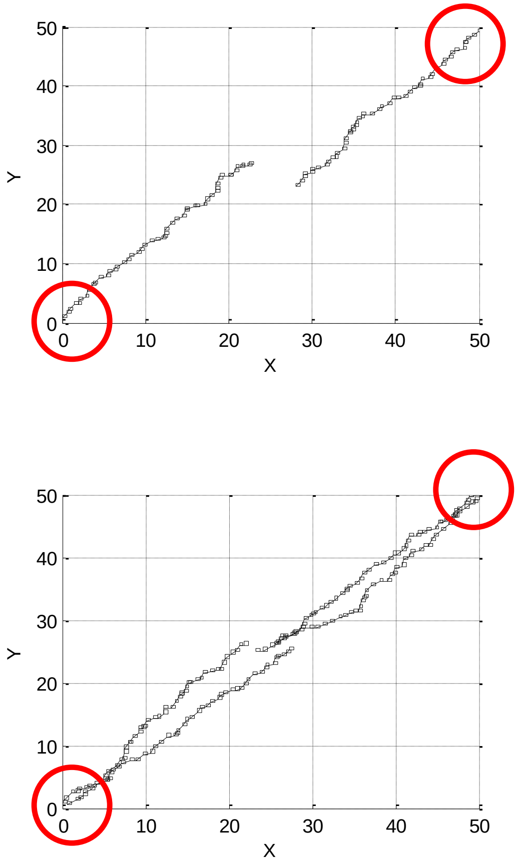
$$p_{\uparrow\downarrow}^{(t)} = p_{\downarrow\uparrow}^{(t)} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

- *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.*

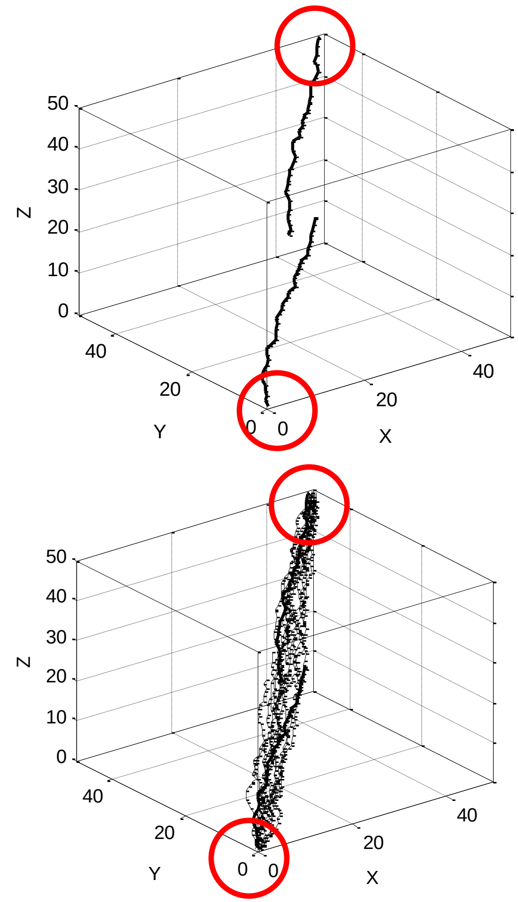


Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security



2D problems

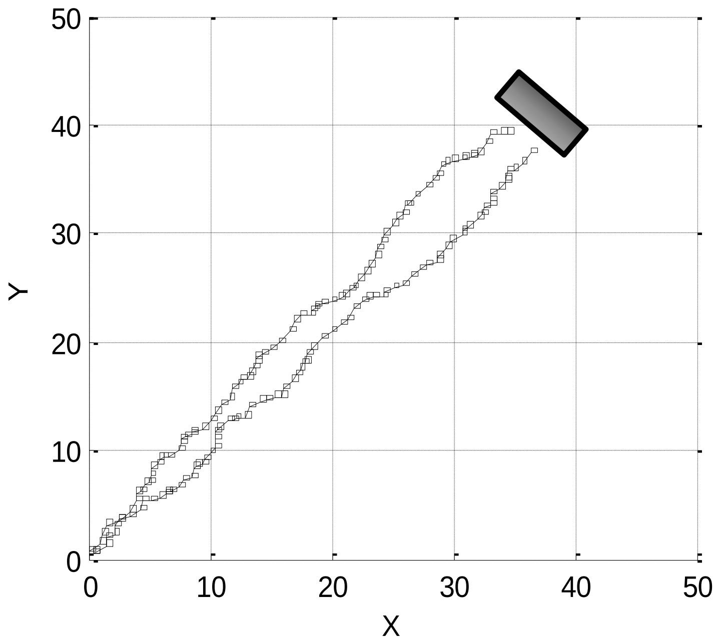


3D problems

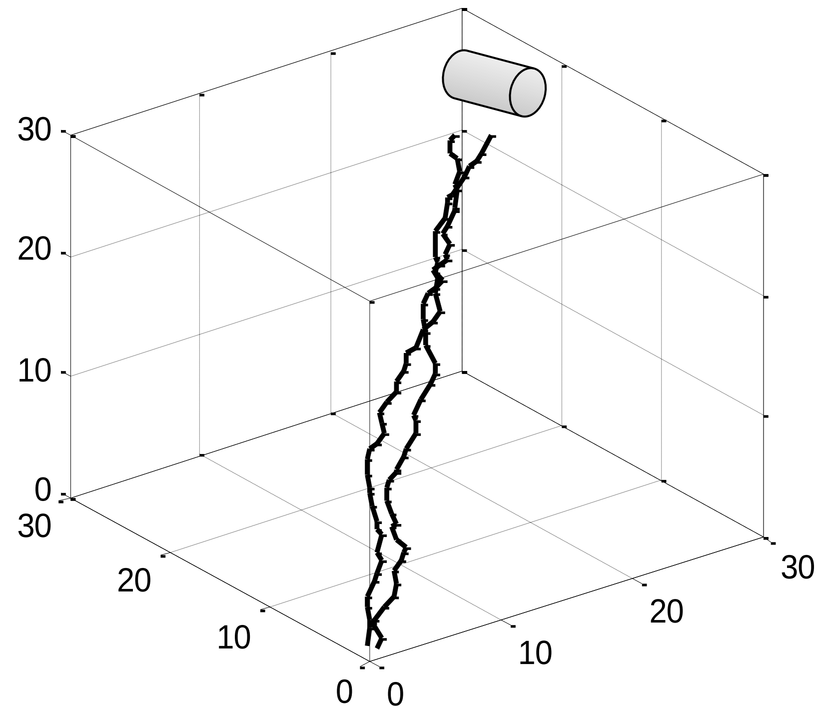
Autonomous Vehicles finding each other with no communication

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 Entanglement of Autonomous Vehicles for Cyber-physical security



2D Simulation

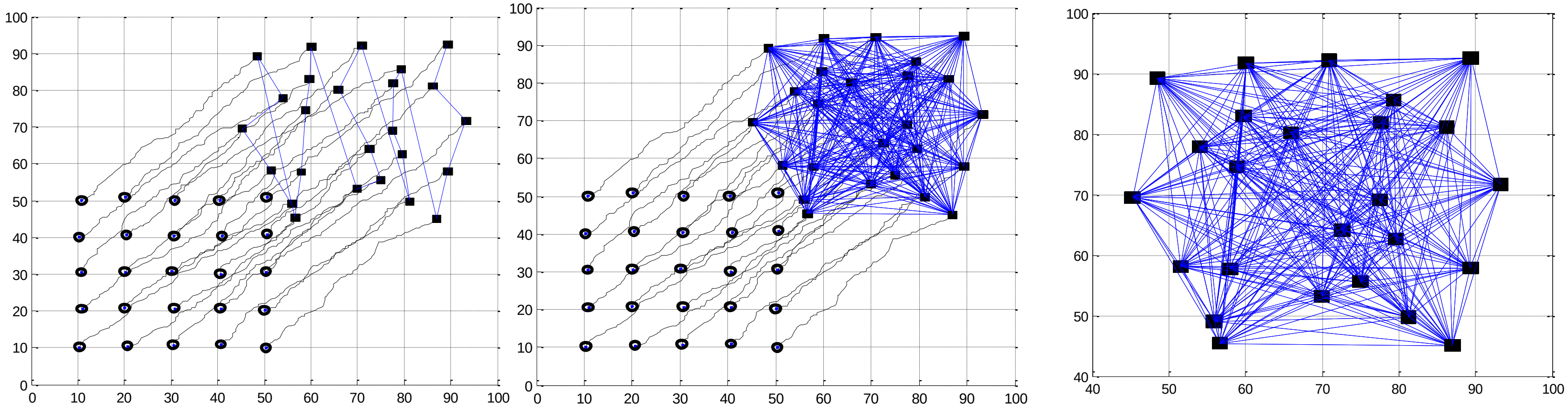


3D Simulation

Autonomous Vehicles performing a task (pushing an object) with no communication.

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.

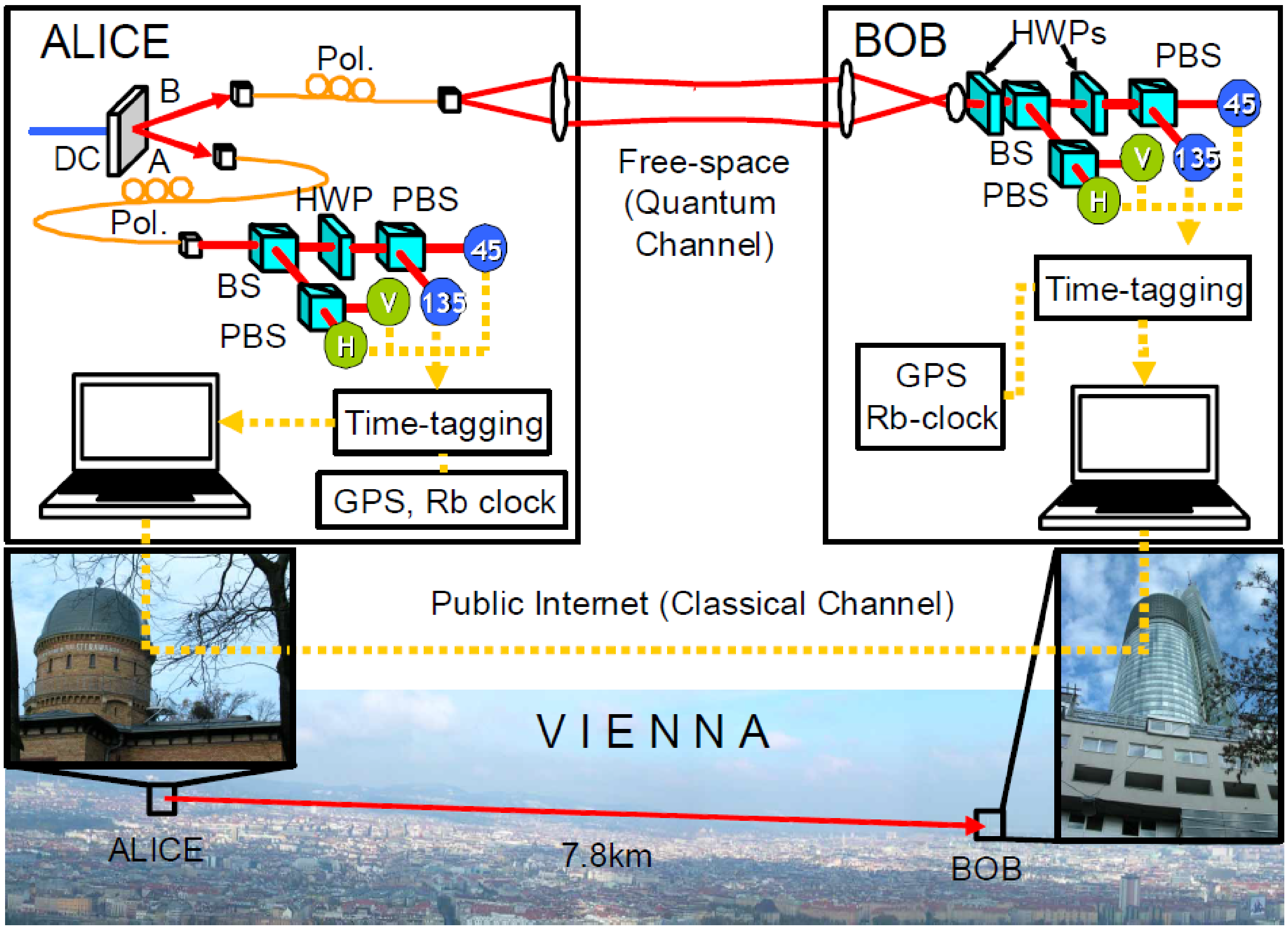
Quantum Network of Autonomous Vehicles for Cyber-physical security



- **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, Ibrahim I. Esat, Clarence W. de Silva, **An Analytical Framework for Quantum Network of Cooperative Unmanned Autonomous Agents**, Frontiers of Information Technology & Electronic Engineering, Submitted.

Quantum Entangled Communication



Quantum Entangled Communication

ARTICLES

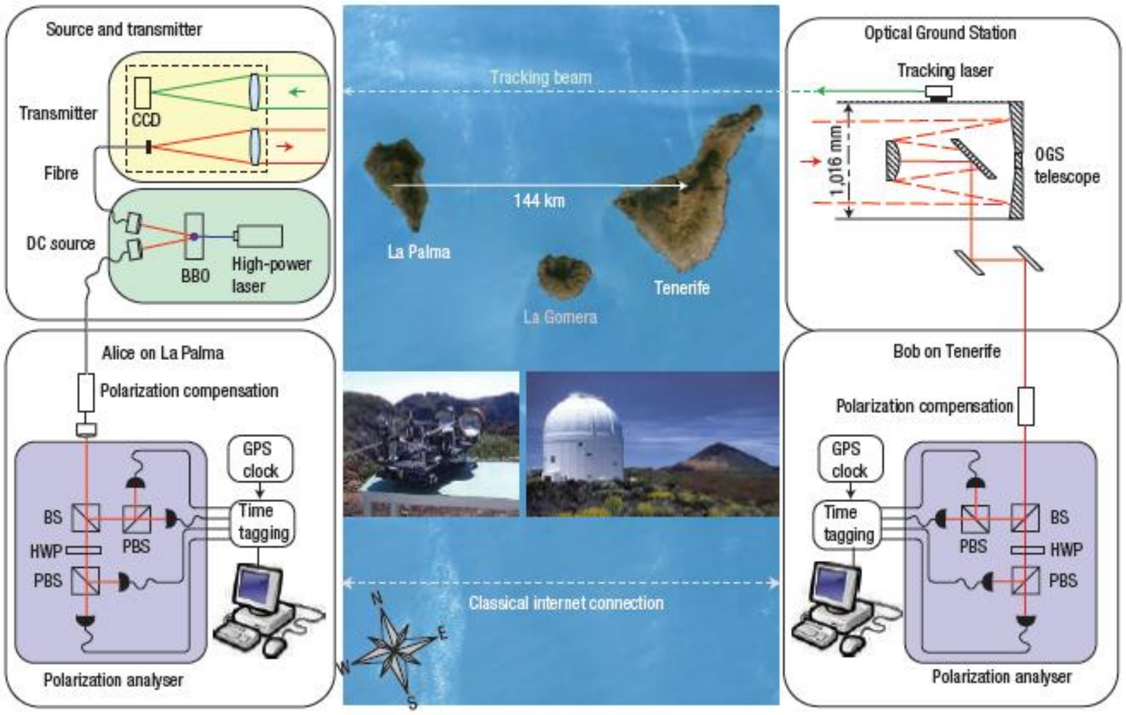
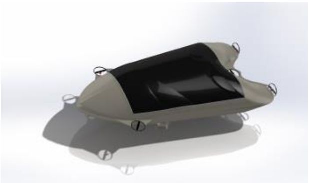
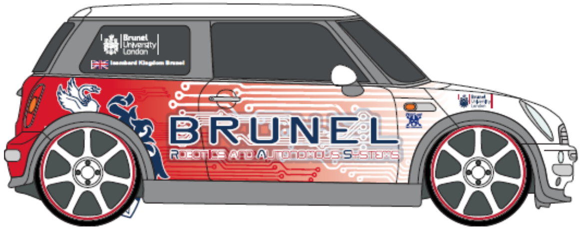


Figure 1 The free-space link between the Canary Islands La Palma and Tenerife in a picture taken from a satellite (clouds are shown here). Polarization-entangled photon pairs were produced in a type-II parametric down-conversion (DC) source by pumping a β-barium-borate crystal (BBO) with a high-power ultraviolet laser. One photon was measured locally on La Palma; the other one was sent through a 15 cm transceiver lens over the 144 km free-space optical link to the 1 m mirror telescope of the Optical Ground Station (OGS) on the island of Tenerife. The link was actively stabilized by analysing the direction of a tracking beam (532 nm) sent from OGS to La Palma, which was received in a second lens focusing it on a CCD (see Fig. 2). No optical cross-talk occurred in the quantum channel, because the tracking laser was sent in the opposite direction; additionally, interference filters were used. Both parties were using four-channel polarization analysers, consisting of a 50/50 beam-splitter (BS), a half-wave plate (HWP) and two polarizing beam-splitters (PBS), which analysed the polarization of an incident photon either in the H/V or in the $+/-45°$ basis, randomly split by the BS. Time-tagging units were used to record the individual times at which each detection event occurred relative to a timescale disciplined by the GPS. Already during data taking, Bob transmitted his time tags via a public internet channel to Alice. She found the coincident photon pairs in real time by maximizing the cross-correlation of these time tags using fast time-correlation software.

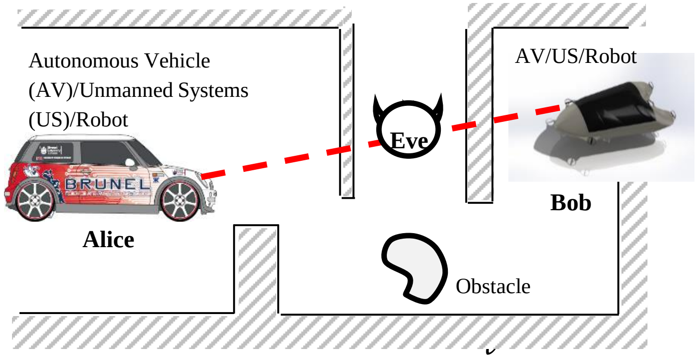
Entanglement experiment for autonomous vehicles
Parametric Down-Conversion

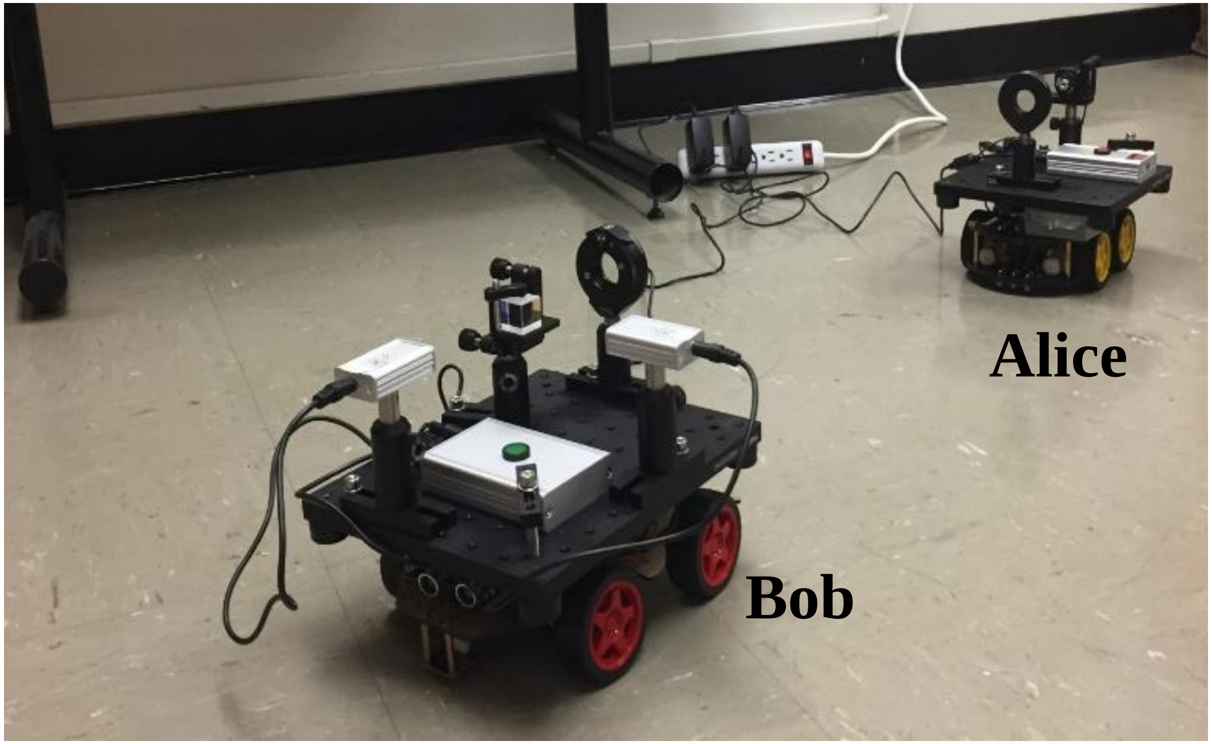




Quantum Entanglement (QE) and Cryptography (QC) experiments for autonomous vehicles

QE by Spontaneous parametric down-conversion (SPDC)





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

Ref: Farbod Khoshnoud, Ibrahim I. Esat, Clarence W. de Silva, Marco B. Quadrelli, **Quantum Network of Cooperative Unmanned Autonomous Systems**, Unmanned Systems journal, Accepted.

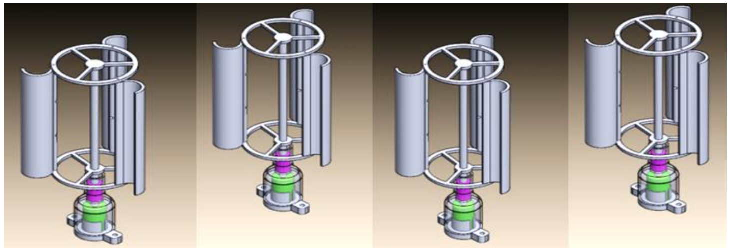
Quantum Entanglement (QE) and Cryptography (QC) experiments for autonomous vehicles

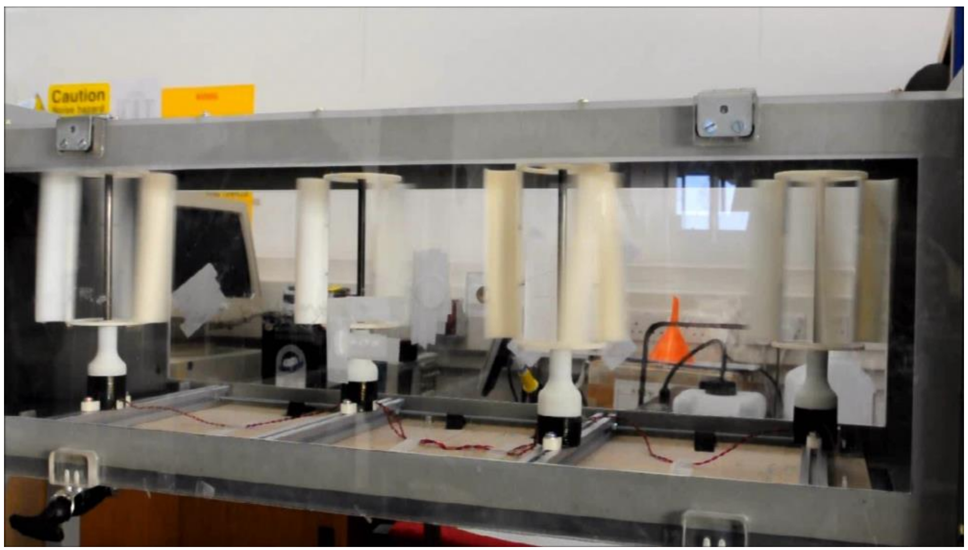
QE by Spontaneous parametric down-conversion (SPDC)

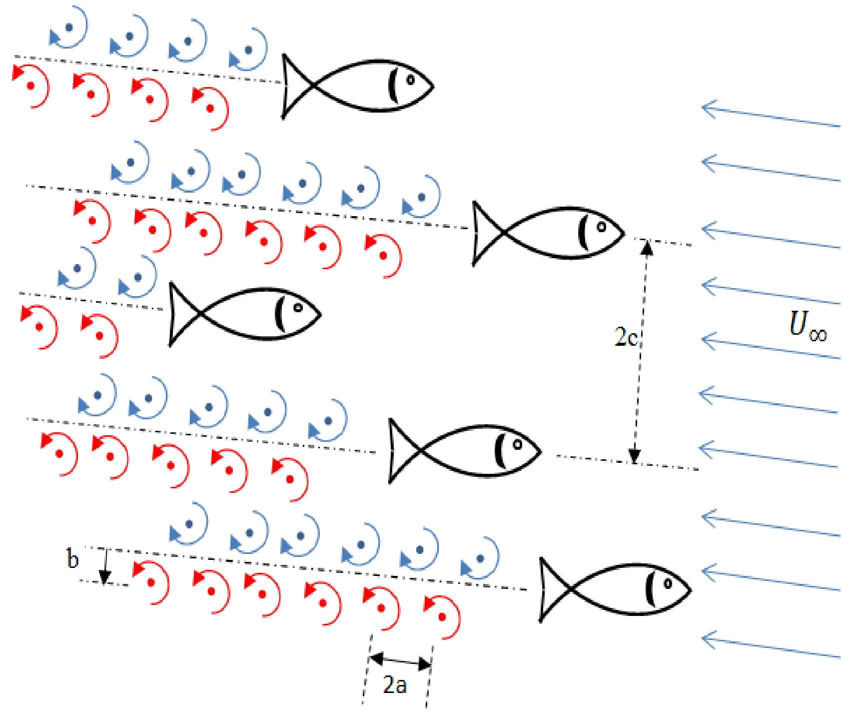
Ref: Farbod Khoshnoud, Ibrahim I. Esat, Clarence W. de Silva, Marco B. Quadrelli, **Quantum Network of Cooperative Unmanned Autonomous Systems**, Unmanned Systems journal, Accepted.

Ref: Khoshnoud F, Esat, I. I., de Silva, C. W., Quadrelli, M. B., 2019. **Quantum robots: Experimental Quantum entanglement and cryptography for robotics**, in progress.

Bio-inspired Vertical Axis Wind Turbines





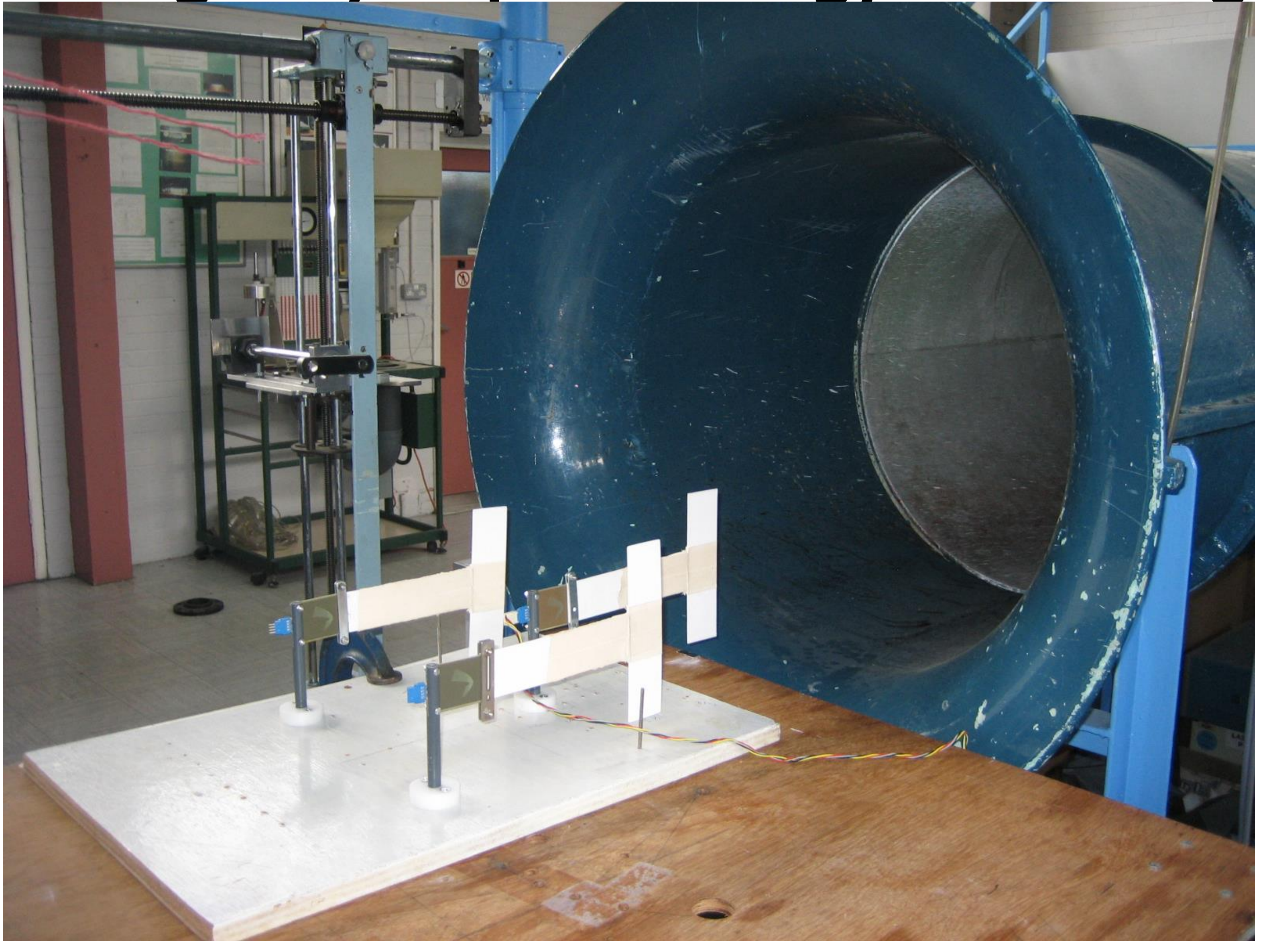


MEng Students: Ahmad Mustaqim Abdullah, Nurul Sofia Suhaimi, Siti Nuraisyah Razali, Nuramira Khairuddin, Muhammad Harith Asari, Amirul Norizan

Video Link

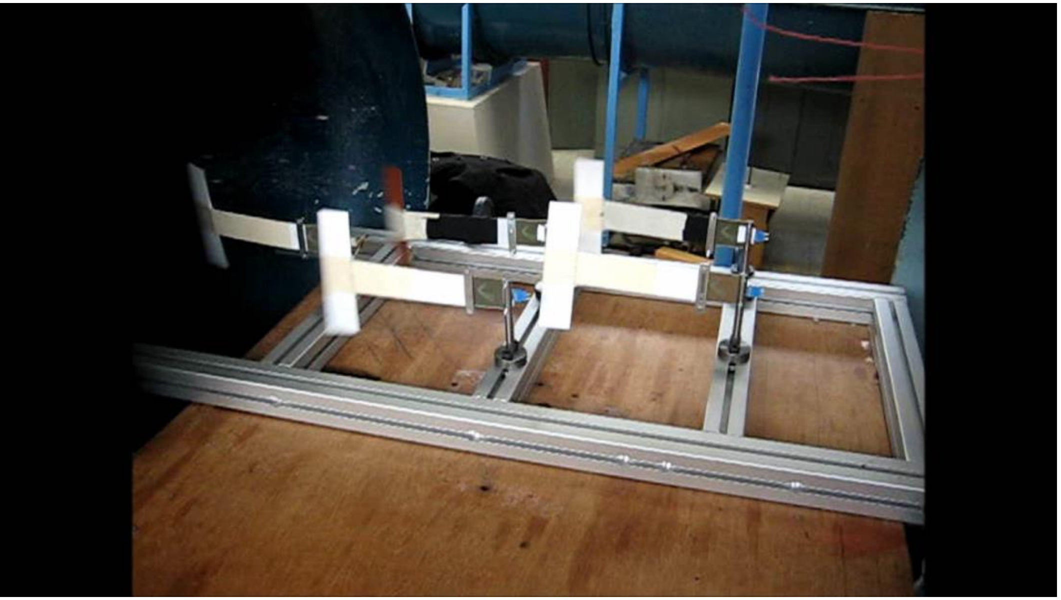
Farbod Khoshnoud, M. M. McKerns, C. W. De Silva, I. I. Esat, R. H.C. Bonser, H. Owhadi, **Self-powered and Bio-inspired Dynamic Systems: Research and Education**, ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, Arizona, USA, 2016.

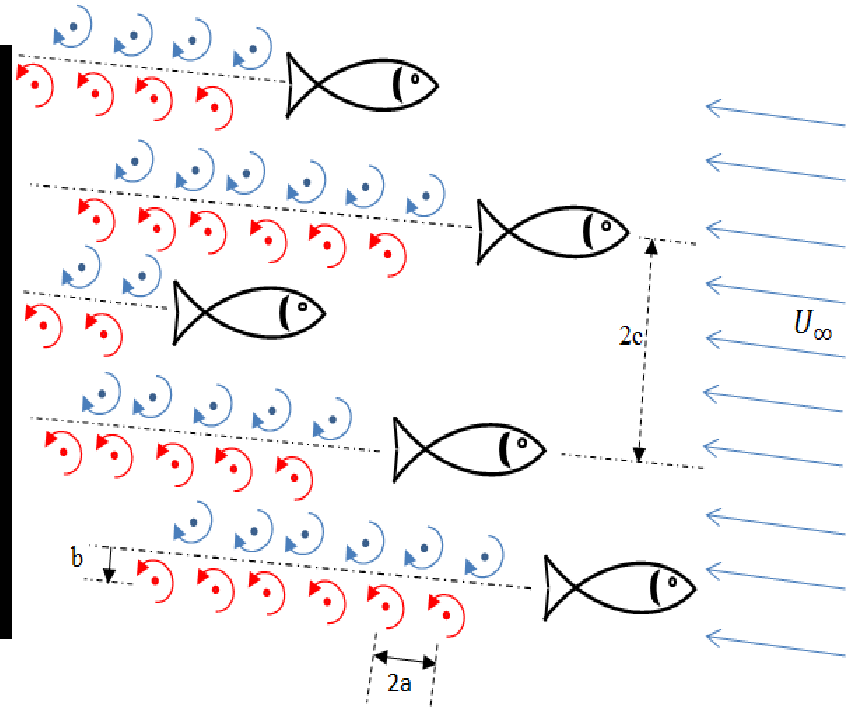
Biologically Inspired Energy Harvesting



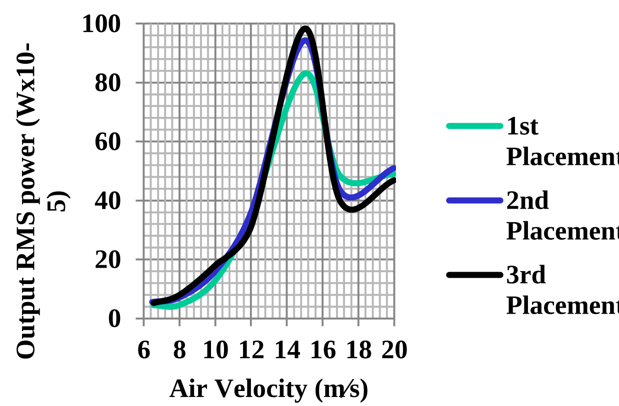
Farbod Khoshnoud, Houman Owhadi, Clarence W. de Silva., etc, **Bio-inspired piezoelectric energy harvesters**, in progress.

Bio-inspired Piezoelectric Energy Harvesters



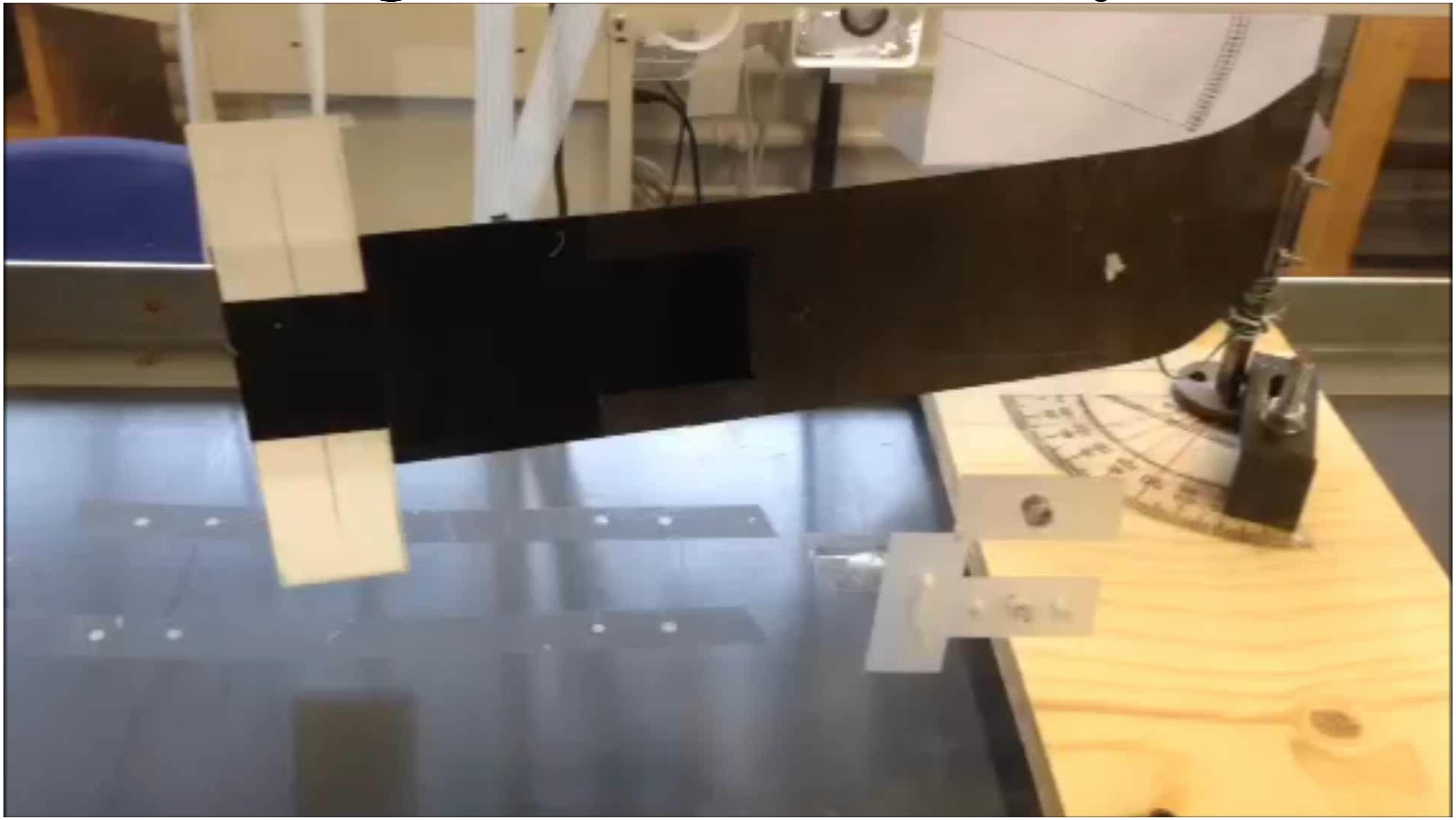


[Video Link]



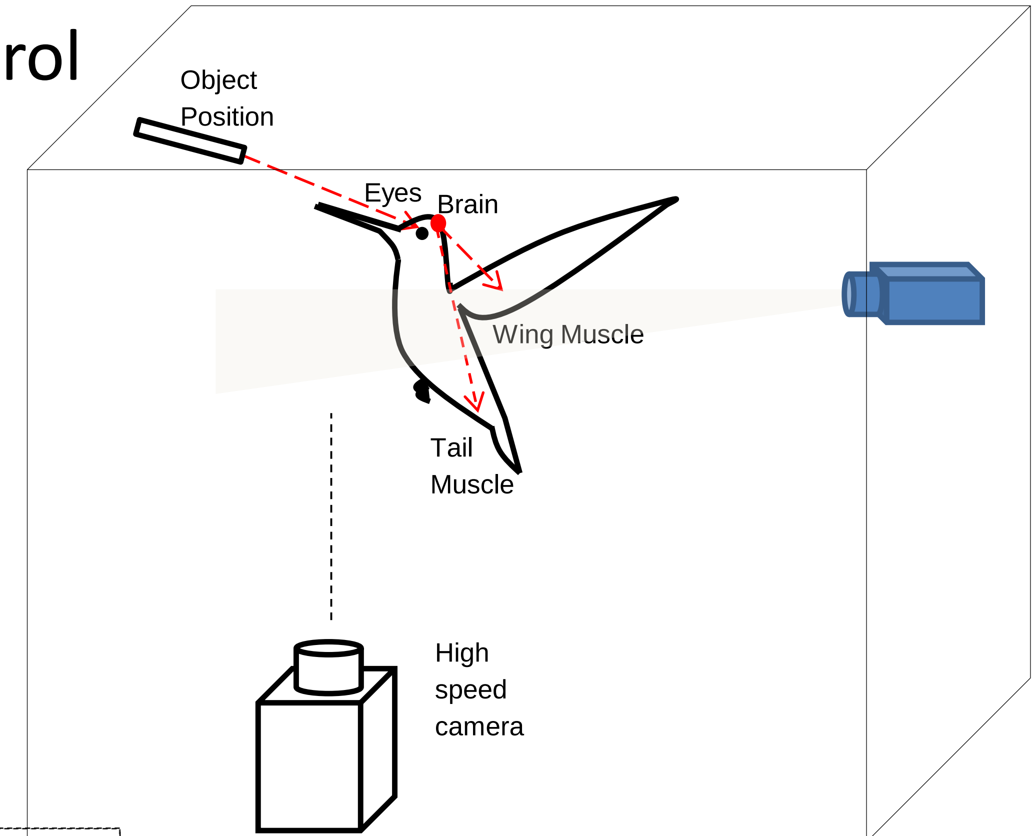
Farbod Khoshnoud, A. Shahba, O. Riaz, R. Shah, R. Shimura, Y. K. Chen and G. Gaviraghi, **Piezoelectric energy harvesting for airships and investigation of bio-inspired energy harvesters**, 5th European Conference for Aeronautics and Space Sciences, Munich, Germany, 1-5 July 2013.

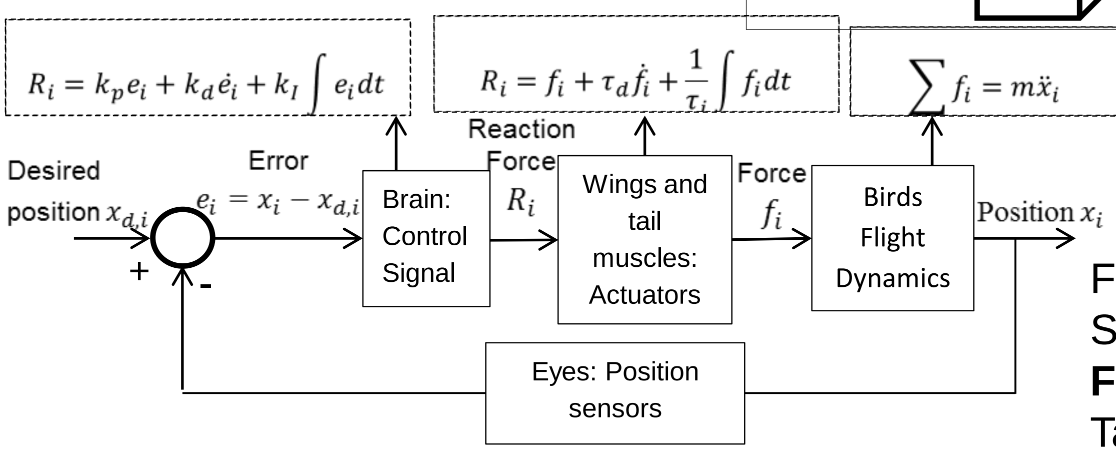
Bistable piezoelectric energy harvesting – Wind tunnel experiment



Video Link

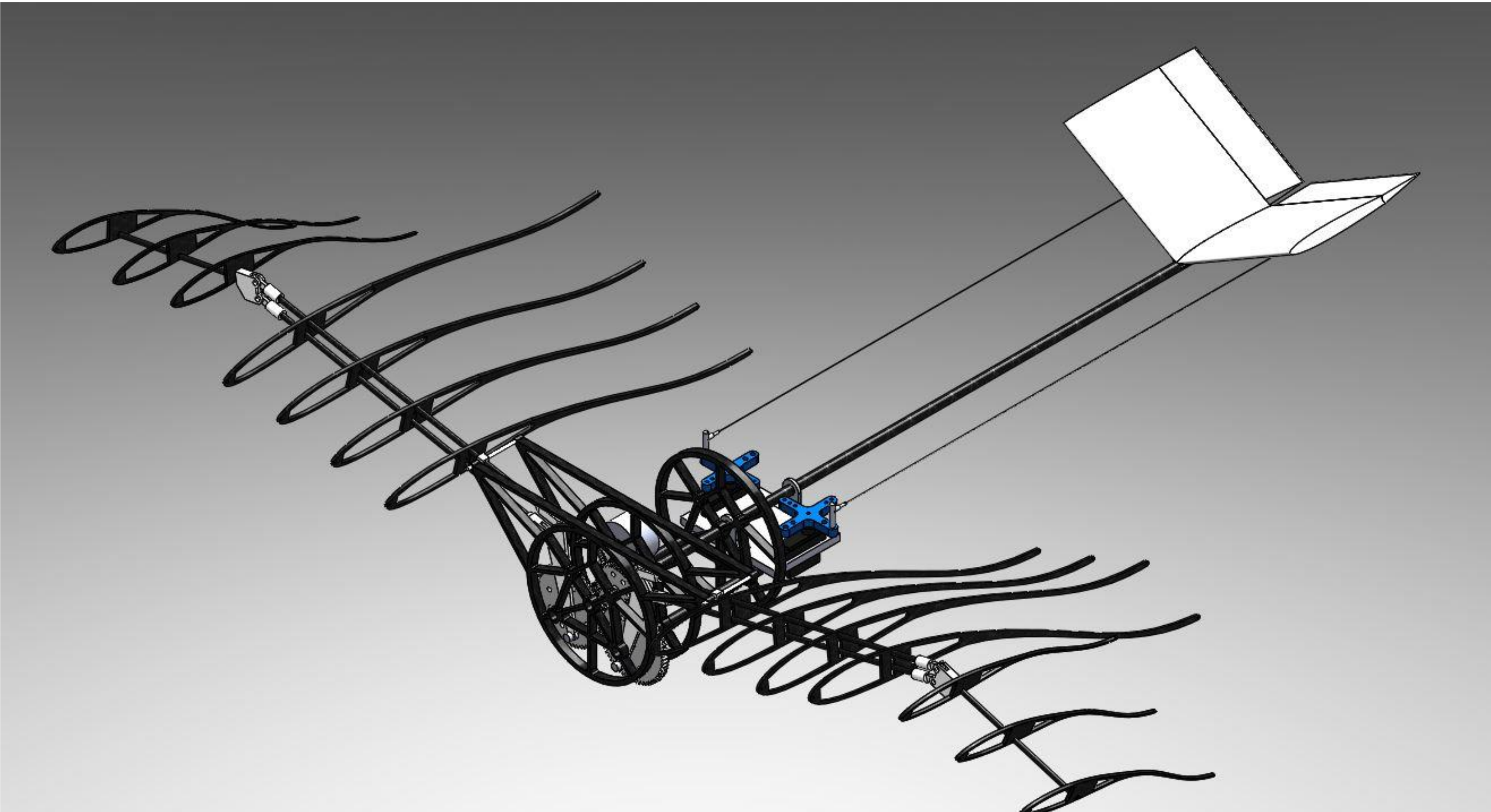
Bio-inspired Flight Control





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

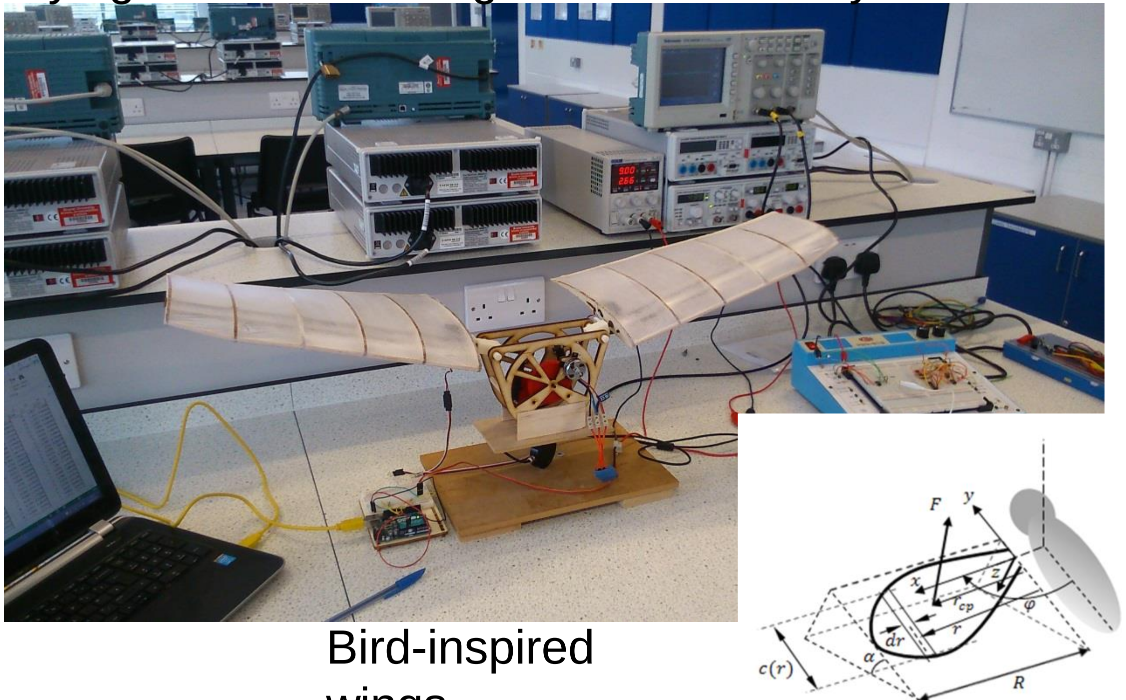
Bio-inspired flying vehicles



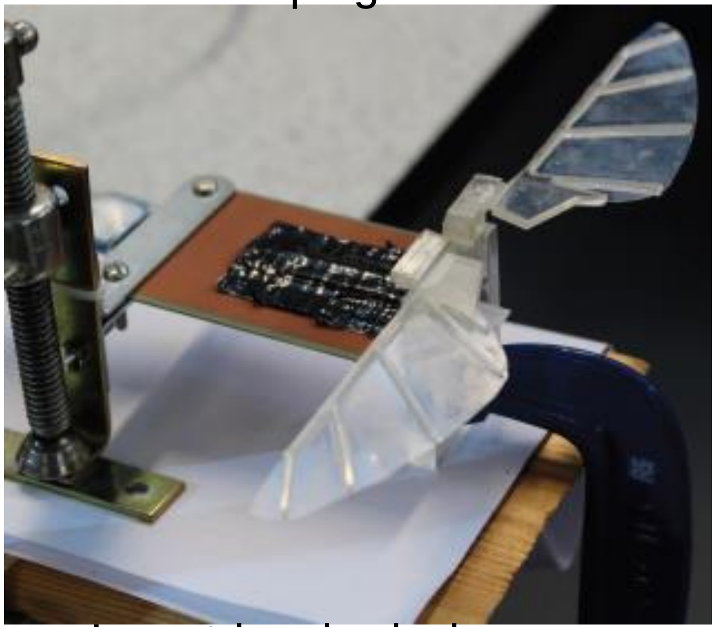
Students: Daniel Popa, Hla Awamleh, Sam Knight, Hugo Larsen, Daniel Sackey, Harshad Raje, Richu Varguese, Valentina Peci

Bird- and insect-inspired flapping wing flying robots

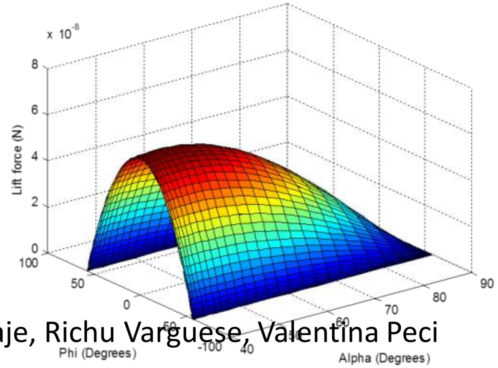
There is no fixed-wing aircraft with agility and manoeuvrability of a bird or insect.
Bird- and insect-inspired flapping wing flying robots: allows developing flying vehicles with high manoeuvrability.



Bird-inspired wings



Insect-inspired wings



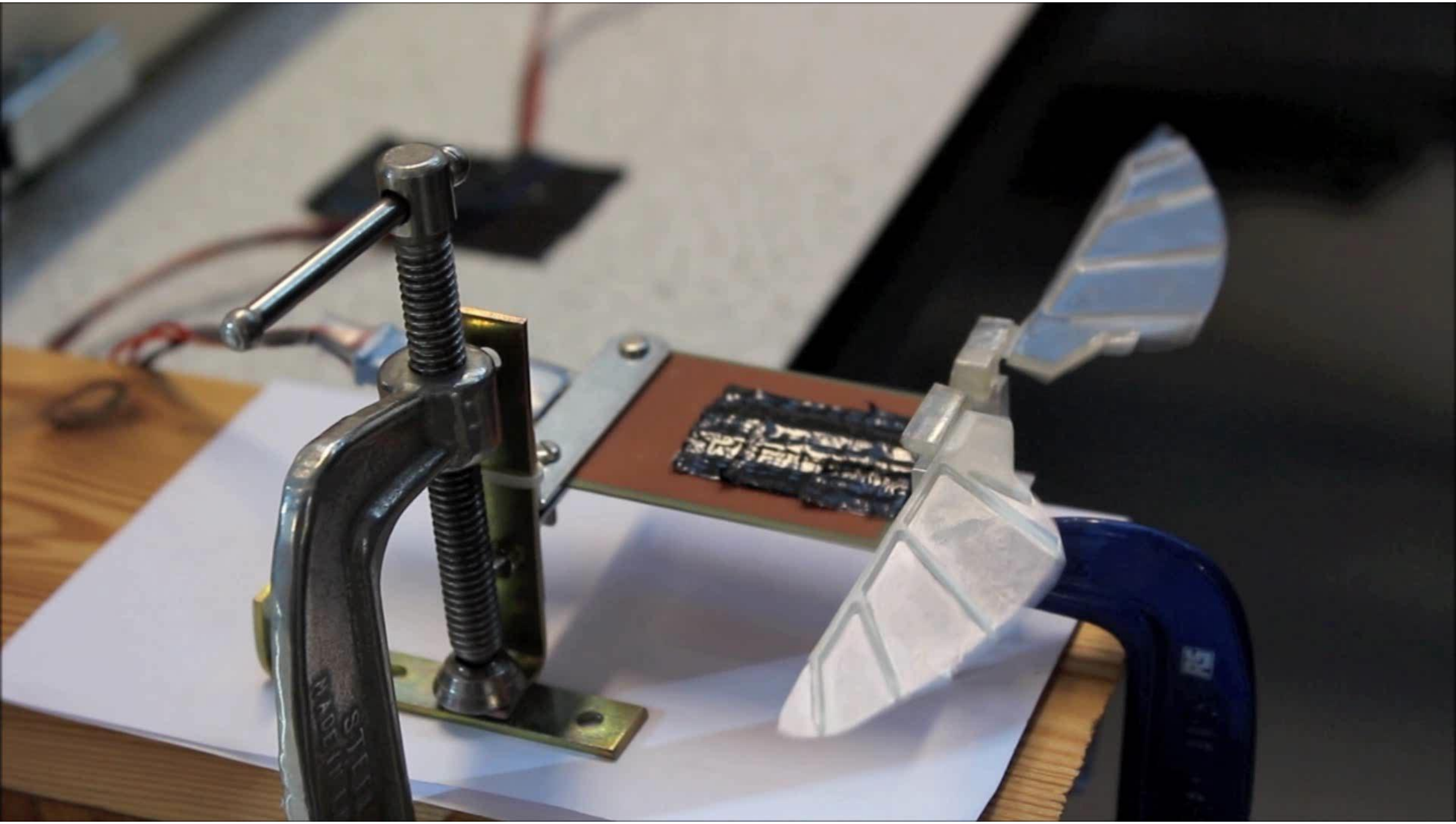
Lift force $F_L = \frac{1}{2}\rho \bar{c} R^3 r_s \int_0^{\pi} C_{L_{max}} \sin(2\alpha(x))\, \Phi^2 \omega^2 \cos^2 x \, dx$

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

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

Insect-inspired flapping wing Micro Air Vehicles:

Piezoelectric actuation and flexible hinge mechanisms



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.

MSc Student: Hugo Larsen, 2015

Video Link

Optimal Uncertainty Quantification

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:

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

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

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

Acknowledgment

CAL POLY POMONA
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ROYAL ACADEMY OF ENGINEERING

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Innovate UK
Technology Strategy Board

Brunel Research and Innovation Fund Award

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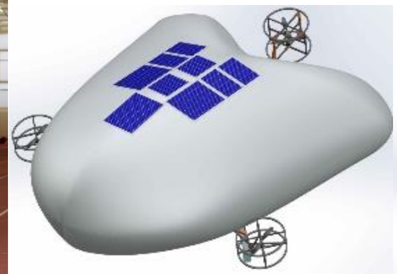

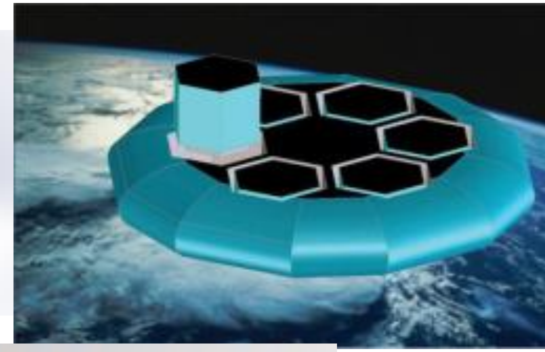

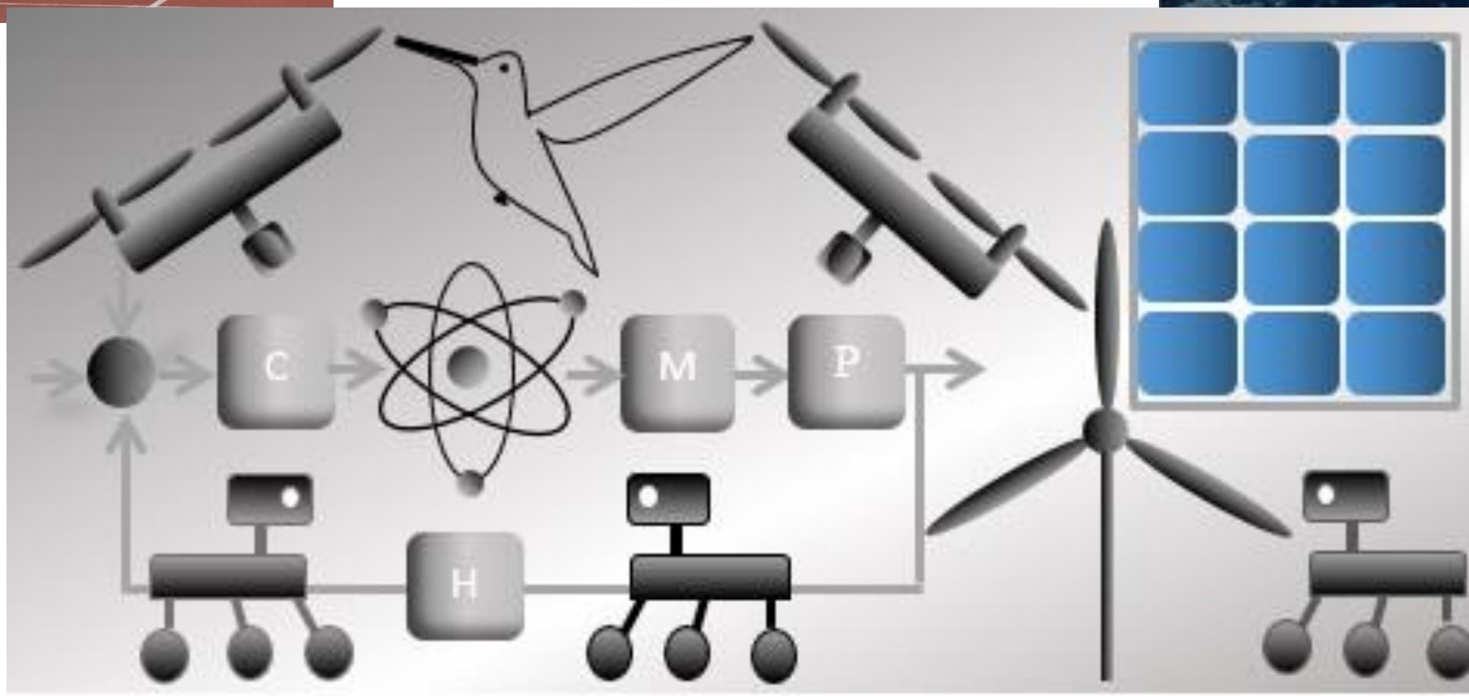

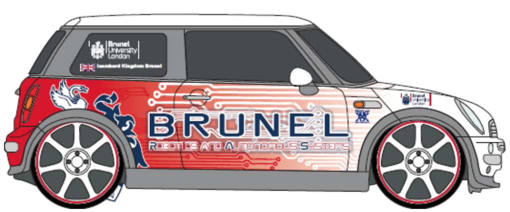

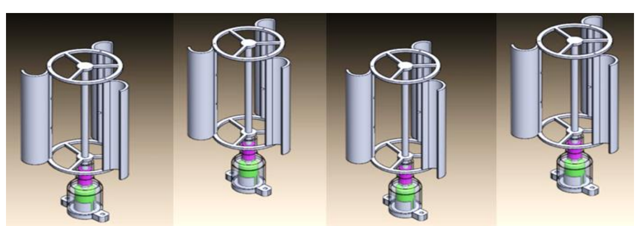

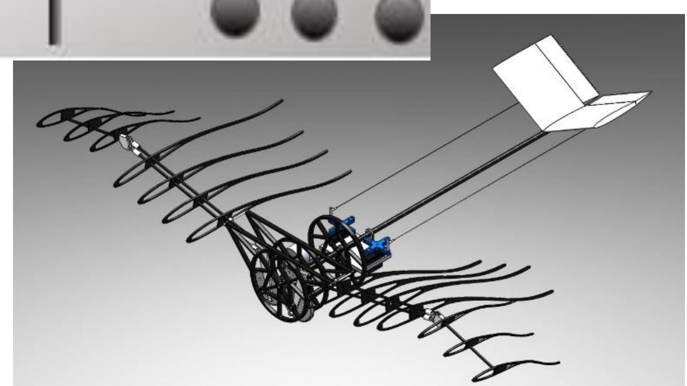

https://www.cpp.edu/faculty/fkhoshnoud/index.shtml