

Capitalising on Australian Space Technology and Innovation

By

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Australian Universities have proven to be innovative and productive in developing technology for space applications. The lack of strategic partnerships and lack of national agreements with major space Agencies has resulted in Australian innovations being adopted for exploitation without a return to Australia.

An example RMIT University Nano X-Ray diffraction technology is used on all European Space Agency space vehicles and probes where star tracker navigation is employed. Australia (unlike Canada) is not a co-operating member state of the European Space Agency with the result Australian Companies and Universities cannot tender as the prime contractor in ESA calls for contracts. At best Australian Universities and companies may be able to form a partnership with a European Company to bid for a contract, but experience has shown instead the Australian innovation is adopted by the winning company and as Australia has no means to develop the idea the technology is acquired at an undeveloped price rather than enhanced value by the technology being matured in Australia with the expertise staying in Australia.

A further example is that Australia has one of the foremost experts in dynamics and control of space systems, including space tethered systems (Prof Pavel M. Trivailo, RMIT University). His research group for example has proposed a novel method for placing spacecraft around target planets during planetary flyby without consuming any propellant, developed a concept of using space tethers for capturing payloads in space and developed methods of optimal control of spacecraft formations and robotic manipulators. His most recent research has been used by the European Space Agency ESA in the 2007 space mission and will be used by the Japan Space Exploration Agency JAXA for a soon to be launched project. Lack of priority and mechanism for teaming and investment in Australian space research has resulted in technology gain for European countries and Japan with minimal benefit to Australia. This project could have been contracted through ESA [1] under an agency reciprocal agreement if Australia was a member. Space Agencies have mandates that require them to prioritise the member state(s). NASA in the USA, JAXA in Japan and other single nation space agencies have a mandate to serve and benefit their national interest. In contrast to the single nation agencies, ESA with its 17 member and co-operating member states is mandated to serve **all** the member states. The mandate of ESA is an opportunity for Australia to benefit from the ESA mandate of distribution [1, 4, 5] to member states. The fact that ESA is a consortia offers an opportunity to Australia who like Canada (Since 1978, Canada has participated as a Co-operating Member State in activities and programs of the European Space Agency (ESA), especially in the design of Earth observation and communications satellites. In June 2000, Canada renewed its membership for another ten year period.).

The benefits to Canada of cooperating member status were reviewed in 2004 by the Canadian Audit, Evaluation and Review Directorate [1], The Directorate found, "*Several technologies and skills have been developed and improved through the participation of Canadian companies in ESA programs. Some businesses have integrated these technologies into products, allowing them to sell these products in markets other than European ones. **Our surveys showed that the economic spin-offs totalled \$128.3 million, a return of 1.27 times the amount invested.** In addition to generating revenues, the development and improvement of space technologies also created or maintained specialized jobs...*"

The advantage to Australia by being a co-operating member state is that ESA is required to distribute its contracts proportionally to member states. Australia would be able to win contracts as prime contractor or leading sub contractor in our areas of expertise. Another benefit as a co-operating member state is that ESA has a highly developed Technology Transfer Division that assists member states in the spin off technology to space and non space applications, facilitating maturity and commercialisation of promising innovations from member states. From 1997 to 2003 Canada [1, p33-34] created or enhanced over 27 technologies using its membership ability to bid for and win ESA research and design contracts. Direct contracts

from ESA under the Agreement provided investment to Canada to develop these technologies, and to improve and refine the development of technologies.

Despite Australia declining an invitation to join as a co-operating member at the same time the offer was made to Canada, the attractiveness of Woomera as a testing centre for project Aurora (ESA's Mars Mission) may provide the opportunity to reactivate the invitation.

Existing Australian Space Activity of World Class Standard

Space Research at RMIT University includes the following projects (non grant funded) that are space related technologies that have high risk of being lost to offshore. All of these are of interest to current ESA and NASA, DARPA calls for contracts. More than half of the current research areas below are three years or less to maturity projects the balance are longer term

- Space tether control technology, Design (including conceptual design, dynamics and control) of the Space tethered systems and innovative technologies
- Dynamics and control of space robotic systems
- Dynamics, control and structural health monitoring for large space structures and flexible systems
- Control system for satellite constellations
- Advanced Wind turbine technology (applications to extraterrestrial planets as well as earth)
- Astronaut Inertial Navigation System (Originally developed for team player sports but ESA already looking at using this technology to space as well as sport, there is a high risk the inventor will have to go overseas (Europe) since Australia cannot be prime contractor as it is not an ESA member or co-operating member state.)
- Inflatable Antenna technology (applicable to "Future soldier" as well as space)
- Clotting of Blood Plasma in Oxygen atmospheres
- Fire Extinguisher for use in micro gravity (has spin offs to earth fire fighting)
- Advanced technology low cost rocket system
- Dual fuel hypersonic air breathing surface compression to orbit space propulsion (space tourism, missile systems, extends flight envelope beyond capability of HYSHOT SCRAM JET) with Grollo Aerospace.
- High lift first stage to orbit space craft (military/ tourism) with Grollo Aerospace.
- Space suit trauma management and control system
- Lunar space suit dust management technology
- Solar panel dust and thermal management technology
- Active materials clothing technology
- Pollination of plants in space and other worlds (has relevance to global Bee extinction crisis)
- Active Counter pressure space glove
- Passive Counter pressure space glove (Technology already lost to USA)
- Nano X-Ray diffusion grating (Technology already lost to Europe)

If only one of the above is successfully adopted for prime contract or technology transfer as a member state the potential financial and "knowledge base" return is substantial.

Measures of Excellence in Australian Space Activity

Two **Luigi Napolitano Awards** from the International Astronautical Federation for Excellence in Space Technology Research awarded to C. Blanksby and P. Williams (<http://www.iafastro.com/index.php?id=199>).

This is a remarkable achievement and recognition, because there were only 15 Awards given by the IAF, including TWO given to Australians - both former RMIT University PhD students and research fellows under the Leadership of Professor Pavel Trivailo.

2007 Paul Williams (Australia)

- 2006 Carlo Menon (Italy)
- 2005 Nicola Baggio (Italy)
- 2004 Julie Bellerose (USA)
- 2003 Veronica de Micco (Italy)
- 2002 Stefano Ferreti (Italy)
- 2001 Noboru Takeichi (Japan)
- 2000 Frederic Monnaie (France)

1999 Chris Blanksby (Australia)

1998 Michael Donald Ingham
1997 G.W.R. Frenken (Netherlands)
1996 W. Tang (China)
1995 O.G Liepack (Germany)
1994 Ralph D. Lorenz (UK)
1993 Dr. Shin-Chin Nishizawa (Japan)

RMIT Space Research Leaders Prof Pavel Trivailo and Assoc Prof Lachlan Thompson are Corresponding Members of the International Astronautical Association. Prof Pavel Trivailo is the Coordinator of the IAF Committee on Materials and (Space) Structures Assoc Prof Lachlan Thompson is the Secretary of the IAF Space Education and Outreach Committee. Assoc Prof Thompson is Contingent Leader for the Australian Team to the International Space Olympics (Australia Gold medallists in 2006 (first time Australia competed) and 2007.

RMIT University is a corporate Member of the International Astronautical Federation
RMIT University is a corporate member of the Australian Space Research Institute

2006 Sarah Connell and Melinda Blake (Australia) winners Cosmonauts Prize for Space Research at the International Space Olympics, Korolev, Russia. (17 countries competing including Russia, USA, UK and Germany).

Realistic and Effective Solution

To effectively solve the cross sector technological and organisational challenges it is recommended that:- **Australia join the European Space Agency as co-operating member state.** *(Note this can be achieved without compromise of defence or trade agreements [2] with the USA, and encourages trade agreements with the European Union.)*

It is also recommended that Australia start occupying its seat (vacant during Howard Government) on the UN Committee for the Peaceful Use of Outer Space. This would allow Australia to be recognised and acknowledged as an active member of the global space fairing nations.

Advantages to Australia of Joining ESA:

The benefits to Australia as a co-operating member state with ESA are:

- Australian companies and Universities will be able to bid and win ESA contracts as as prime contractor in key technology areas.
- The Australian innovations and technologies listed above will be eligible to be considered for funding and development, rather than be lost due to lack of national focus, funding mechanism. Allowing an expansion of Australia's capability.
- European investment helps build the expertise within Australia strengthening national expertise at minimal cost. As shown by Canada [1] should Australia win a prime contractor role for even a small component, European investment will build infrastructure in Australia.
- Terms of the ESA agreement of member states must return 90% of Australia's membership fee back in project and contract work to Australia. Canada [1] was able to build on this to regain 127% plus new business and markets.
- Co-operative membership state with ESA will provide Australia with a proven means [1] for the wide and diverse range of space research in Australia to attract and find access to development funding.
- Australia can leverage its ESA co-operating member state to access ENVISAT [1, 3] for earth and environmental mapping data including high quality data on water tables, and subsurface water. It is worth noting that an effective earth resources and environmental monitoring satellite costs in excess of 500 million Euro. Australia at the present does not have the technology to design and build an effective environmental satellite. However technology sharing as an ESA associate member will allow cross trading in areas where Australia is strong in space technology to build expertise.
- Should Australia join as an co-operating member state, then an option would be that CSIRO with appropriate funding and direction take on the role (interim or otherwise) of

representing Australia's space science and technology at ESA without the need to expend additional funds on infrastructure to form an "Australian Space Agency".

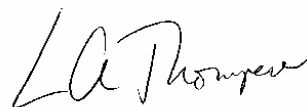
- A Co-operative Member status with ESA still allows for Australia like Canada to have agreements with other space Agencies [2]. Yet opens European space technology markets to Australia [1].
- Australia gains access to the ESA Student Outreach Educational program with the financial support of the students from Australian Universities attending the International Astronautical Federation Congresses.
- Australia gains valuable investment capital and infrastructure investment with real expertise [1] growth, helping establish space industry technology companies not just know how but also processes and materials working towards a "gifted nation" in both research and TAFE/VET.

Consequences of NOT Joining ESA as a co-operating member state

If Australia does not form strategic partnerships as a co-operative member state and charts of course of developing its capability internally the funding cost is enormous. The result would be small "hobby Projects" that support enthusiastic and well meaning teams with little hope of a lasting benefit or technology gain. A useful environmental satellite such as ENVISAT costs 2 billion Euros [1]. There is the cost of ground support infrastructure, Astronomical societies and interest groups will push for major telescope projects costs 100's of millions of dollars. What needs to be thought about is how to facilitate the best return to our nation for what is invested. Canada has proven [1] that new for a modest membership fee, the Canadian government facilitated access for Canadian companies and Universities the ability to gain ESA (European) investment in their technologies, new businesses and infrastructure. The results of Canada's initiative are shown by the dollars with a 127% return on investment. Canada has built important and valuable satellite design and imaging technologies [1] in contrast over the same period Australian activity has been limited to bit player roles in Optus Satellites and FedSat. Satellite technology is highly advanced and expensive the cost of ENVISAT was 2 Billion Euro, in contrast a small team of Australians developed and launched FedSat at a government cost [6, 7] over \$20 million. The enormous cost to achieve an effective and useful satellite for Australia is at present beyond our national capability both financially and technologically. However Australian capability and technology can be grown comparatively quickly and enhanced in a cost effective manner by forming strategic partnerships such as an ESA co-operative membership. Our farming community [8] is crying out for aid now on water management, Existing Satellites like ENVISAT can provide important immediate information at a cost effective level with Australia as a co-operative member state. Allowing Australian space researchers to concentrate on innovating and developing space technologies where they have a genuine expertise and advantage to bring investment, markets and resources to Australia.

- Small self interested Australian bodies will aggressively compete in a counter productive manner for the limited funding Australia can provide. The consequences of this are the dissolution of funds and technology.
- Continued drain to Europe and USA of Australian talent and ideas.
- Australia will loose financially and intellectually [1].
- Neighbouring regional powers are investing heavily in space technology i.e.; China, India, Korea and South Africa will make Australia technologically irrelevant.

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3. C. de Cooker, Head of International Relations ESA, "ESA enlargement – special relations with Central and Eastern European countries", ASD Annual Convention, Barcelona, 4-5 October 2007
4. J. Dordain, Director General ESA, "Submission by the European Space Agency in Response to the Commission Public Consultation Reforming the Budget, Changing Europe", [ESA/C\(2007\)18](#), Paris 2007.
5. B. Zufferey, "The Plan for European Co-operating States (PECS), *Towards a new partnership between ESA and Romania*", Solar-Terrestrial Interaction workshop, Sinaia, 8 September 2005
6. R. Hill, "Defence to manage FedSat", Aust Gov ministerial press release 205/5 23 Dec 2005.
7. S. Cauchi, "Australia blasts back into space game", The Age, December 12 2002.
8. B. Lagan, Australian farmers face water cuts as drought crisis worsens, Times Online, April 19, 2007.

Attachments

CV Assoc Professor Thompson

CV Professor Pavel Trivailo

Evaluation Report er-0405-0202 (separate file: er-0405-0202.pdf)

Attachments:

Associate Professor Lachlan Thompson FIEAust, IAA CM

Research Leader of Space Flight Vehicle Systems Engineering conducts research into space technology design, in particular development of new and innovative technologies which include "Pollination of Plants in Space and Micro Gravity". In 2006 he spent his sabbatical leave at the European Space Agencies ESTEC facility in the Netherlands. He was the principle Investigator for the STARS *Spiders in Space*, which flew on the space shuttle STS-107 Columbia, a Microgravity experiment he designed with the Melbourne Zoo, Glen Waverley Secondary College and RMIT University. Inventor and designer of the Mars Surface Laboratory at the Victorian Space Science Education Center and Chairman for the 5th Australian space Science Conference, Melbourne Sept 2005. His research includes space trauma systems, active counter pressure space glove and the application of Inertial Navigation System (INS) for Astronauts on Mars. His research also includes space propulsion technologies and hypersonic space planes with Grollo Aerospace.

Lachlan's sporting research includes the design using space technologies of the world's fastest Olympic bicycle for the Australian Institute of Sport. The "Superbike" ridden by the Australian Cycling Team including Shane Kelly and Kathy Watt was the winner of twenty-six World UCI Championship Titles from 1994 to present. In addition his team has assisted the Australian sailing team in their quest for gold at the 2000 Olympics. Research leader for new technology sledges developed and used in the 1998/99 Icetrek Antarctic Expedition of Hillary, Philips & Muir. Assoc Prof Thompson is the contingent Leader for the Australian Space Olympics Team in 2006 and 2007. He is also a Judge on the Cosmonaut and Space Experts Panel for the International Space Olympics in Korelov Russia in 2006, 2007 and 2008.

Keynote Address

1. **L. A. Thompson**, "The Challenges of Space Education", 5th Australian Space Science Conference, Melbourne, Sept 2005.

Journal Publications

2. N. M. Mathers, **L. A. Thompson**, "Using Inflatable Antennas for Portable Satellite-Based Personal Communications Systems", International Astronautics Federation, ACTA, ISSN 0094-5765, France, Oct. 2007.
3. **L. A. Thompson** and N. M. Mathers, "Spiders in Space, Collaboration between Teaching and Research", Science Education Journal, EMBL, Germany. May 2006.

Seminars and Workshops

4. Brumfitt A.E., **Thompson L. A.**, et al., "Space, Teacher Classroom Resources for Early Primary Years", ECIS, Nice, Nov 2006.
5. Brumfitt A.E., **Thompson L. A.**, et al., "Venus Express a Mission for Education, Classroom resources workshop for teachers and scientists", Europlanet, Berlin, Sept 2006.

Refereed Papers

6. E. Jens and **L.A. Thompson**, "Wind Energy for Use on Other Planets", 59th IAC, Glasgow 2008. ,
7. **L.A. Thompson**, M. Blair and M. Grollo, "Space Research Launch Vehicle Development in Australia", 59th IAC, Glasgow 2008.
8. **L. Thompson**, W. Van DeGuer and A. Brumfitt, "University High Power Rocketry at Woomera Rocket Range Australia", 59th IAC, Glasgow 2008.
9. **L. Thompson** and A. Brumfitt, "International Space Camps a Proven Formula for Informal Education", 59th IAC, Glasgow 2008.
10. A. Brumfitt, **L. Thompson**, Et'al, "Sustainable Space Education Resources and Teacher Support Across the Classroom for all Teachers", 59th IAC, Glasgow 2008.
11. **L. Thompson** and A. Brumfitt, "Small Sounding Rocket Program Scouts and Guides", ASRI Conference , Melbourne, Nov 2007.
12. A. Brumfitt, **L. Thompson** and A. Martynov, "The International Space Olympics", 58th IAC, Hyderabad, India Oct 2007.
13. A. Brumfitt and **L. Thompson**, "New structures and mechanisms for space educational outreach", 58th IAC, Hyderabad, India Oct 2007.
14. A. Brumfitt and **L. Thompson**, "40 Million Scouts and Guides celebrate Sputnik 50th Anniversary", 58th IAC, Hyderabad, India Oct 2007.
15. A. Brumfitt and **L. Thompson**, "Winning the International Space Olympics", AMEC, Peth, July 2007.
16. Brumfitt A.E., Bandechi, M., and Thompson L.A., "CDF Inroads to Education", 2nd

- Concurrent Engineering Conference, ESA-ESTEC, Netherlands, October 2006.
17. N. M. Mathers, **L. A. Thompson**, A. E. Brumfitt and P. Honan, "Bees in Space: Creating a buzz about space science", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 18. A. E. Brumfitt, **L. A. Thompson**, "Scouts and Guides Forefront users of 21st Century Space Technology", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 19. N. M. Mathers, **L. A. Thompson**, A. E. Brumfitt and P. Honan "Making the Exploration of Space a Reality for Everyone", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 20. N. M. Mathers, M. K. Pakakis, A. E. Brumfitt, and **L. A. Thompson**, "Victorian Space Science Education Centre: A State of the Art Resource for the Whole Community", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 21. A. E. Brumfitt, **L. A. Thompson** and D. Raitt, "The Art of Space Mission Patches and their Origins in Society", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 22. N. M. Mathers and **L. A. Thompson**, "Inflatable Antennas in Terrestrial and Extraterrestrial Environments", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 23. N. M. Mathers, M. K. Pakakis, **L. A. Thompson**, and A. E. Brumfitt, "Victorian Space Science Education Centre: Communicating Space to the Community", 57th IAC, International Astronautics Congress, Valencia Spain, Oct 2006.
 24. A. E. Brumfitt, L. Christensen and **L. A. Thompson**, "Dedicated Space Science Education Centres Provide the Model for Effective Outreach", Europlanet, Berlin, Sept 2006
 25. N. M. Mathers and **L. A. Thompson**, "Bees on Space - Flight and Pollination in Microgravity" STAVCON 2005, Australia, Nov 2005.
 26. N. Saks, **L. A. Thompson**, "TOAST SAT: Awesome Satellite Design Project for Secondary Schools", STAVCON 2005, Australia, Nov 2005.
 27. C. Van der Velden, C. Bil, **L. Thompson**, I. Noome, "Hyperion Space Education Opportunities Through International Partnerships", 56th IAC, Fukuoka, Japan, Oct 2005.
 28. N. M. Mathers, **L. A. Thompson**, "Using Inflatable Antennas for Portable Satellite-Based Personal Communications Systems" 56th IAC, Fukuoka, Japan, Oct 2005.
 29. N. M. Mathers, **L. A. Thompson**, and P. Honan, "Bees in Space: "An Opportunity to Inspire the Next Generation", 5th Australian Space Science Conference, Melbourne, Sept 2005.
 30. C. Van der Velden, C. Bil, I. Noome, **L. Thompson**, "The Hyperion Project: International University Collaboration in Spacecraft Design Education", 5th Australian Space Science Conference, Melbourne, Sept 2005.
 31. N. M. Mathers, **L. A. Thompson**, "Applications for Inflatable Antennas in Terrestrial and Space Environments" 5th Australian Space Science Conference, Melbourne, Sept 2005.
 32. P. Spencer, M. Pakakis, **L. A. Thompson**, N. M. Mathers, "Victorian Space Science Education Centre: A Science Platform for Young Australians" 5th Australian Space Science Conference, Melbourne, Sept 2005.
 33. M. McLean, **L. A. Thompson**, "Flinders Christian Community College and Lighthouse Christian College: Bees in Space: A Mission to Mars" 5th Australian Space Science Conference, Melbourne, Sept 2005.
 34. M. Pakakis, P. Spencer, **L. A. Thompson**, and N. M. Mathers, "Walking on Mars The Victorian Space Science Education Centre", AMEC V, ACT, Australia, Aug 2005.
 35. N. M. Mathers, **L. A. Thompson**, and P. Honan, "Bees in Space: "An Education Innovation" CONAST54", Melbourne, Australia, July 2005.
 36. M. Pakakis, P. Spencer, N. M. Mathers, *L. A. Thompson*. "The Victorian Space Science Education Centre", CONAST54", Melbourne, Australia, July 2005.
 37. N. Mathers, **L. Thompson**, and K. Ghorbani, "Using Inflatable Structures Technology for Portable Land-based Communication", AIAC, Melbourne, May 2005.
 38. C. Van der Velden, **L. A. Thompson**, and C. Bil, "New Frontiers for Space Technology Education in Australia", AIAC, May 2005.
 39. **L. Thompson**, G. Carstairs, Et'al, "*STS107 Columbia and Spiders in Space*", 54th International Aerospace Congress, Bremen, September 2003.
 40. **L. Thompson**, N. Mathers & T. Kancharakpan, "*Reinventing the Wheel, a Novel Approach to Long Duration Space Habitat*", AIAA, Wright Centenary Congress, Dayton Ohio, July 2003.

41. N. Mathers, **L. Thompson**, K. Ghorbani titled "Development of inflatable feed horn for parabolic dish antenna" at the 8th Australian Symposium on Antennas.
42. **L. Thompson**, G. Carstairs, "STS107 Columbia, Spiders in Space Experiment", NSSA 3rd Australian Space Science Workshop, July 2003.
43. N. Mathers, **L. Thompson**, K. Ghorbani, "Inflatable feed horn for inflatable parabolic dish antenna", NSSA 3rd Australian Space Science Workshop, July 2003.
44. **L. Thompson**, C Bil, N Mathers "Teaching science "Spiders in Space Experiment" Columbia STS 107" 14th AaeE Conference and the 9th Australasian WIE Forum Melbourne 2003
45. K. Jones, **L.A. Thompson**, et'al, "*Manufacture of Composite materials in Space*", 7th Australian Space Development Conference, Sydney, 15th –17th July 2002.

Professor Pavel M. Trivailo

Prof. P.M. Trivailo has been the Project Leader for a few successful projects (ARC-DI, DSTO and European Space Agency) on *aerial, underwater and space cable towed systems*. His Group, for example: has developed advanced cable models and extremely fast and versatile simulators for the DSTO aerial decoys/targets and DSTO unmanned underwater vehicle (UUV) Wayamba and performed design for the space tethered system launched and deployed by ESA in 2007 and to be launched and deployed by Japanese Space Exploration Agency JAXA in 2009.

Prof. P.M. Trivailo has proposed, developed and applied: methods of optimal constrained trajectory planning and dynamic analysis of space tethers and manoeuvred cable and other elastic systems; optimisation of multiple cooperative systems (spacecraft formations and space robotic systems); multi-objective control methods for optimisation design of flexible structures, enabling significant improvements in the capability of smart control and damage detection for such structures and co-rotational finite element method for reconfigurable complex flexible systems. Prof. Trivailo, together with two research fellows, has used Virtual Reality design and optimisation methods to produce the world-first "Mach-5" ballistic system, which has been manufactured and successfully tested at the DSTO's Woomera launching facilities.

He has 85 inventions for original mechanical designs. He has also programmed numerous computer packages for structural design and optimisation, including a commercial AutoCAD-based FEM pre-processor for aerospace design companies and Virtual Reality interactive simulation tools.

1.2 Other evidence of impact and contributions to the field

Professor Trivailo has 29-years of continuous research and teaching experience in Mechanical and Aerospace Engineering and is an author of 270 papers, research reports and publications, including 85 patents on inventions and a text book "Vibrations: Theory & Aerospace Applications (v.1&2)".

Professor Trivailo is currently the Research Group Leader in Vibrations, Dynamics and Control in the School of Aerospace, Mechanical and Manufacturing Engineering, RMIT. Corresponding Member of the International Academy of Astronautics (IAA) [2006-cur]; the **Coordinator of the Materials and Structures Committee of the International Astronautical Federation (IAF)** (2004-) and a Co-Chair of the "Space Structures: Development & Verification" IAF Symposia (2002-2005), Member of the IAF International Program Committee [1999-cur]; Member of the International Tethered Systems Committee [1997-cur].

He is also an Associated Editor and a Member of the Editorial Boards of the *International Journal on Inverse Problems in Science & Engineering* and *International Journal of Advanced Mechatronic Systems*. In 1998 Prof Trivailo jointly with Dr C.R.Farrar and Dr S.W. Doebbling from Los Alamos National Laboratory organised and conducted a Short Course "State-of-the-Art in Vibration-Based Structural Damage Identification" for Australian engineers/researchers from various organisations, including CSIRO, AMRL, Holden, VUT and Melbourne University. Currently Prof Trivailo is a Senior supervisor for 7 PhD students (4 of them are directly associated with the topic of this application). As a Senior Supervisor he has a record of 18 PhD & Masters successful completions. In recognition of his outstanding contribution to postgraduate students he was awarded "RMIT PhD Supervisor of the Year 2000". In October 1999 the paper co-authored by Prof Trivailo and his PhD student, C.Blanksby, on the control of the tethers for capturing satellites, received the prestigious IAF "Luigi Napolitano" Award for its innovative nature and contribution to space sciences. In October 2007, this prestigious Award has been again given to Prof Trivailo's PhD graduate, Dr P.Williams.

1.3 Recent significant publications (in the past five years - 2003 onwards)

Papers, related to the Space Technology and Towed Systems are marked with a star ()*

Books (2003 onwards only)

1. ***Trivailo P.M.**, Vibrations: Theory & Aerospace Applications, Vol.1&2, RMIT Publisher, Melbourne, 2003.

Articles in Refereed Journals (2003 onwards only)

2. *鳥羽色 波辺留 (トリバイロパベル), マルチフレキシブルロボットマニピュレータ複合システムの非線形モデリング. -日本ロボット学会誌, 2008. Translation of the text before: **Trivailo P.M.** Non-Linear Dynamic Modelling of Composite Systems of Multiple Flexible Robotic Manipulators. Proceedings of the Robotic Society of Japan. (Submitted for publication, February 2008).
3. *Williams, P., and **Trivailo, P.**, "Dynamics of Circularly-Towed Aerial Cable Systems – Part 1: Optimal Configurations and Their Stability," *Journal of Guidance, Control, and Dynamics*, Vol.30, No.3, May-June 2007, pp.753 -765 (13 pp), 40 refs, 8 figs, 3 tables; ISSN 0731-5090. [Published by the AIAA (American Institute of Aeronautics and Astronautics)].
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5. ***Trivailo, P.M.** and Carn, C. "The Inverse Determination of Aerodynamic Loading from Structural Response Data using Neural Networks," - *Inverse Problems in Science and Engineering*, Taylor & Francis, Vol. 14, No. 4, June 2006, 379-395. ISSN 1741-5977 print, ISSN 1741-5985 online.
6. ***Trivailo, P. M.**, Dulikravich, G. S., Sgarioto, D. and Gilbert, T. "Inverse Problem of Aircraft Structural Parameter Estimation: Application of Neural Networks," - *Inverse Problems in Science and Engineering*, Taylor & Francis, Vol. 14, No. 4, June 2006, 351-363. ISSN 1741-5977 print: ISSN 1741-5985 online.
7. ***Trivailo, P. M.**, Gilbert, T., Glessich, E. and Sgarioto D. "Inverse Problem of Aircraft Structural Parameter Identification: Application of Genetic Algorithms Compared with Artificial Neural Networks," - *Inverse Problems in Science and Engineering*, Taylor & Francis, Vol. 14, No. 4, June 2006, 337-350. ISSN 1741-5977 print: ISSN 1741-5985 online.
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Refereed Journal Papers:

1. Williams, P., Watanabe, T., Blanksby, C., Trivailo, P. and Fujii H.A., **Libration Control of Flexible Tethers Using Electromagnetic Forces and Movable Attachment** - *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 5, September–October 2004. Published by the AIAA (American Institute of Aeronautics and Astronautics) and having an Impact factor of 1,000 (2003), this Journal is one of the most prestigious (if not the most) international journals, with unique specialisation in the Guidance, Control and Dynamics niche area of Aerospace Engineering.

Due to the Google Scholar, this paper has already attracted 12 citations.

This paper proposes utilizing the distributed Lorentz forces that are induced in an electromagnetic tether as a control actuator for controlling the tether motion. The control input governing the magnitude of the applied actuator force is the current being conducted within the tether. A wave-absorbing controller

is also proposed to suppress the unstable high-order modes that tend to be initiated by electromagnetic forces. The absorption of traveling waves along the tether can be achieved by proper movement of the tether attachment point on the main satellite. A mission function control law is presented for controlling the tether length and in- and out-of-plane librations, derived from a model that treats the tether as an inextensible rigid rod. The control law is numerically simulated in a continuum model of the tether system. It is shown that the out-of-plane motion of the tether can be effectively damped by appropriate control of the tether current for inclined orbits. The presence of tether flexibility causes significant bowing of the tether that grows into instability of the lateral modes. It is shown that this instability can be effectively suppressed by applying the proposed wave-absorbing controller for deployment, retrieval, and stationkeeping scenarios.

2. Williams, P., and Trivailo, P., (2007)
**“Dynamics of Circularly Towed
 Aerial Cable Systems –
 Part 1: Optimal Configurations and
 Their Stability;
 Part 2: Transitional Flight and
 Deployment Control,”**

*Journal of Guidance, Control, and
 Dynamics*, Vol.30, No.3, May-June 2007,
 pp.753 -765 (13 pp), 40 refs, 8 figs, 3
 tables; ISSN 0731-5090.

*Journal of Guidance, Control, and
 Dynamics*, Vol.30, No.3, May-June 2007,
 pp.766 -779 (14 pp), 43 refs, 26 figs, 3
 tables; ISSN 0731-5090.

The paper develops an innovative and unconventional idea, developed from the conceptual design to the “ready to use” detailed technology. The article describes a novel, intelligent system for manoeuvring a cable towed from an air vehicle (aircraft, glider, UAV), to the desired destination (off-ground, land or water surface or underwater) with near zero relative velocity. The system has outstanding accuracy, reliability and safety, and will be operable in almost any conceivable scenario. This system will add substantially to Australia’s capability to rapidly reach remote locations and is far superior to conventional systems. A very important application of the technology is in applying it to the **bushfire suppression**.

3. 鳥口 波辺留 (鳥口波辺留)
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Translation of the text above:

Trivailo P.M.

Non-Linear Dynamic Modelling of Composite Systems of Multiple Flexible Robotic Manipulators.

Proceedings of the Robotic Society of Japan. (Submitted, August 2007).

http://www.rsj.or.jp/index_e.html

This paper presents new results on modelling of the **composite system of multiple space robotic manipulators with highly flexible robotic arms**. A set of various operational scenarios is considered (involving kinematic excitation of the system via

the base motion, collective transfer of the payload and **spinning ejection of the spacecraft**). The paper also presents new results on generic optimal path planning and optimal control of single and cooperative multiple robotic manipulators. For these systems the associated non-linear optimisation problems were formulated in this paper and solved using the Legendre-pseudospectral method. More importantly the method allows not only to minimise the specified arbitrary non-linear cost function, but also allows to solve the optimisation task in view of the **multiple additional non-linear constraints**. Examples of the additional constraints may involve path constraints on the system, prohibiting the members to enter a specified space area or on the contrary, prescribing the system to follow the desired trajectory or prescribing for the members of the robotic system not to leave the allowed bandwidth "corridors".

4. Williams, P., Blanksby, C., and Trivailo, P. (2004)
"Tethered Planetary Capture Maneuvers,"
Journal of Spacecraft and Rockets, Vol. 41, No. 4, July-August 2004, pp. 603-613.
 ISSN: 0022-4650.

The paper is printed in the international journal, **with unique specialisation in the Spacecraft and Rockets niche** area of Aerospace Engineering.

This paper is significant in the field of tethered satellites because it proposed a **novel method for placing spacecraft around target planets during planetary flyby without**

consuming any propellant!

It also showed that the technique can be used during solar system tours to allow the mother satellite to generate a combined gravity-assist and momentum-enhanced orbital boost. It was the first paper on such a technique to be published and provided a comprehensive analysis of the maneuver. It also showed that the mass of tether required to perform the maneuver is less

than the required fuel to perform the maneuver at a single planet. This means that multiple maneuvers save significant fuel. This momentum-exchange technology could revolutionise the way future space exploration is undertaken.

Due to the Google Scholar this paper has already attracted 7 citations.

Published by the AIAA (American Institute of Aeronautics and Astronautics) and having an Impact factor of 1,000 (2003), this Journal is one of the most prestigious (if not the most) international journals, with unique specialisation in the Guidance, Control and Dynamics niche area of Aerospace Engineering.

This **work has significant implications for the dynamics design and analysis of complex aerospace and automotive systems.**

Parameter estimation of dynamical systems governed by ordinary differential equations is formulated as a discrete nonlinear programming problem. The dynamical constraints are transcribed as a set of equality constraints that are driven to zero by a sparse sequential

- Williams, P., Sgarioto, D., and Trivailo, P. (2006)

"Optimal Control of an Aircraft-Towed Flexible Cable System,"
Journal of Guidance, Control, and Dynamics,
Vol. 29, No. 2, 2006, pp.401-410,
ISSN 0731-5090.

- Williams, P., and Trivailo, P. (2005)
"Optimal Parameter Estimation of Dynamical Systems using Direct Transcription Methods,"
Journal on Inverse Problems in Science and Engineering.
Taylor & Francis. - Vol 13, No. 4, 2005, pp.377-409.
ISSN Print: 1741-5977; ISSN Online: 1741-5985.
[<http://www.tandf.co.uk/journals/titles/1>

quadratic programming algorithm. Five different transcription methods are examined: Heun's method, Hermite–Simpson, 5th degree Hermite–Legendre–Gauss–Lobatto, pseudospectral, and a 5th order Legendre–Gauss–Lobatto integration method. To demonstrate the power, features and performance differences of the proposed methods, the parameter estimation algorithm has been applied to four different problems from biochemistry, physics, robotics, and aerospace. Impact Factor of the Journal is 0.672.

Conference Papers:

1. Optimal Control of Aerial Tethers for Payload Rendezvous. *Proceedings of the ASCC-2004 (The 5th Asian Control Conference)*; 20-23 July 2004, Grand Hyatt, Melbourne, Victoria, Australia. Paper #365 - 7 pp; 7 figs; 24 references. ISBN 073-40-3016-9; p.58; pp. 395-403. Web: http://ascc2004.ee.mu.oz.au/paper_submission.html

Due to the Google Scholar this paper has already attracted 12 citations.

The exciting concept of using a tether deployed from an aircraft to rendezvous with a ground-based location is successfully demonstrated in this paper. By manipulating the cable attachment point position and the rate of change of the cable's radial velocity, it can be shown that the tip of a cable being towed behind an aircraft can rendezvous with a surface location. This is achieved through optimal control, using the Chebyshev-pseudospectral method which has excellent accuracy. The results of the optimization found that rendezvous was successful, with all target states being met. The cable tip experiences little motion during the rendezvous maneuver, while the required deployment/retrieval rates are not excessive. Only a **modest amount of control input is required**, mostly at the beginning and end of

the maneuvering, with rendezvous occurring soon after maneuvering commences.

- Blanksby, C. and Trivailo, P.M. (2000), **Assessment of Actuation Methods for Manipulating Tip Position of Long Tethers.**

Original publication:

50th International Astronautical Federation Congress, October 1999, Amsterdam, The Netherlands, Paper IAF-99-A.05.08, pp.1-7.

Then the paper was reprinted by the International Astronautical Federation and an Invited Paper as the Journal Paper in the *Space Technology: Space Engineering, Telecommunication, System Engineering and Control*, (Lister Science, Great Britain, ©2001, ISSN 0892-9270), Vol 20, No. 1, 2000, pp.31-39.

- Williams, P., Blanksby, C. and Trivailo, P. (October 2002) **"The Use of Electromagnetic Lorentz Forces as a Tether Control Actuator,"** - Paper IAF-02-A.5.04. - *53rd International Astronautical Federation Congress/The World Space Congress*, Houston, Texas, U.S.A., 10-19 October, 2002. - 10 pp.

Awarded by the International Astronautical Federation "Luigi Napolitano" prestigious Award for the contribution to the space science. This is one of two only Napolitano Awards given to Australians (with the second Award given to P.Williams – another PhD supervised by P.M.Trivailo).

Partnership offers received from NASA in the USA and Japanese Space Exploration Agency JAXA and European Space Agency ESA.

This paper was presented at the most prestigious space forum – **World Space Congress.**

It is significant in the field of tethered satellites because **it proposed a new use of tethers in space transportation systems enabling the tether be manipulated to rendezvous with incoming payloads.** This paper considers using the distributed electromagnetic force which is induced in a conductive tether as a control actuator for maneuvering the tether tip. Specifically, combinations of lengthrate/tension and current control are examined so as to maneuver the tether tip. This **revolutionary technique** can be also used to transfer satellites from one orbit to another without any propellant involved.

4. Trivailo, P., Williams, P., and Blanksby, C. (July 2002)

"Assessment of the Use of Tether Technology in the Future

Exploration of Mars (Invited

Paper)," - *The 2nd Australian Mars Exploration Conference "Exploring the Red Planet"*. University of Sydney, Sydney, 12-14 July, 2002. - 26 pp.

The exploration of Mars is a noble objective that embodies the human desire to expand our physical and intellectual horizons. This Invited Paper **maps out the role of space tether technology in the exploration of Mars.**

It considers design of low-cost Mars space missions using the following: Efficient braking at Mars using Tethered aerocapture in the Martian atmosphere; Efficient braking on return to Earth using Tethered electrodynamic braking; Tossing payloads between Earth and Mars using tethers; Delivering probes to Mars on interplanetary missions; Generation of artificial gravity in spacecraft for the journey to and from Mars.

EXAMPLE OF PUBLICATIONS ABOUT RESEARCH BY P.M.TRIVAILO IN THE MEDIA:

Detailed publication "Throw me a rope" by David Hambling in the "New Scientist" Magazine (30-April-2005, No. 2497, pp. 35-37) on innovative research in aerial towed systems by Prof P.M.Trivailo and his research Group in the School of Aerospace, Mechanical & Manufacturing Engineering (SAMME), RMIT University.

For a few weeks the web version of this article was listed under "Top Story" [titled as "Flying circles around the helicopter"] on the main Magazine's web:

<http://www.newscientist.com/channel/mech-tech/>

(Current New Scientist adv web version:

<http://www.newscientist.com/channel/mech-tech/mg18624971.600>)

This article generated incredible interest from the engineering community all over the world with numerous partnership proposals.

This article is on the development of a smart tethered systems for civilian and military operations such as firefighting, sea rescue missions and the delivery of supplies to isolated communities. For details refer to the following web:

<http://www.alumni.rmit.edu.au/news/NewScientist.pdf>

New Scientist, The World's No.1 Science & Technology News Service, www.newscientist.com

EXAMPLE OF RECOGNITIONS and SPACE RELATED AWARDS given to Prof P.M.TRIVAILO:

- **2006: He has been elected Corresponding Member of The International Academy of Astronautics (IAA), Engineering Sciences Section.**

The establishment of the International Academy of Astronautics (IAA) was led by Dr. Theodore von Karman, one of the most important figures in the evolution of rocketry, and the IAA's first president. The IAA was founded in Stockholm on August 16, 1960. Since that time, IAA has brought together the world's foremost experts in the disciplines of astronautics (from approximately 65 countries) on a regular basis to recognize the accomplishments of their peers, to explore and discuss cutting-edge issues in space research and technology, and to provide direction and guidance in the non-military uses of space and the ongoing exploration of the solar system.

Currently the IAA Statutes authorized Engineering Sciences Section of the Academy to have **60 Members and 120 Corresponding Members worldwide**. There were only 20 Corresponding Members elected in 2006 to the Academy's "Engineering Sciences" Section worldwide.

- **He has been awarded the Australian Academy of Sciences (AAS) and the Japanese Society for Promotion of Sciences (JSPS) "Scientific Visit to Japan 2007"** research Grant. He was appointed to the position of visiting Professor of Tokyo Metropolitan University/Tokyo Metropolitan Institute of Technology, Japan in June-September 2007 and worked on a several space projects of the Japanese Space Exploration Agency (JAXA), including a rocket launch scheduled for 2009.

EXAMPLE OF PRESENTATIONS given to Prof P.M.TRIVAILO on AEROSPACE TECHNOLOGY APPLICATIONS:

- ✦ Trivailo, P.M. Overview of Innovative Research Projects in Dynamics & Control at SAMME, RMIT University. **Special Technical Presentation** for the Bavarian Government, Technical and Industrial Experts Delegation (Led by Mr Hans Spitzner, Vice-Minister of the Bavarian Ministry of Economic Affairs, Infrastructure, Transport and Technology). RMIT University, Vice-Chancellory, 01 March 2006.

- ✦ Trivailo, P.M. Dynamics & Control of Complex Systems: Overview of Research Projects at SAMME, RMIT University. **Invited Lecture** for students and staff, Tokyo Metropolitan Institute of Technology, October 2005.
 - ✦ Trivailo, P. Non-Linear Dynamics and Control of Complex Systems. **Invited Lecture at Stanford University**, U.S.A., Monday, 27 September 2004, Chaired by Prof. George S.Springer, Paul Pigott Professor of Engineering, Aeronautics & Astronautics;
 - ✦ Trivailo, P. Defence Applications of Research @ RMIT University in Advanced Dynamics and Control. Thursday, 29 July 2004, RMIT University. **Special presentation** for Dr Hsiang (Sean) Yung Yu – Director, US Army Research Laboratory and Lieutenant Colonel Clyton Brown – US Army Liaison Australia;
 - ✦ Trivailo, P. Automotive Applications of Research in Advanced Dynamics, Control & Vibrations @ RMIT University. Friday, 02 July 2004, Pacifica. **Special presentation** for Pacifica's Research Management;
 - ✦ Trivailo, P. Research by RMIT/DSTO Centre of Expertise in Aerodynamic Loading. Friday, 26 March 2004, AVD, Platform Sciences Laboratory, DSTO Australia. **Special presentation** for Major Mitchell, USAF Asian Office of Aerospace Research & Development;
 - ✦ Trivailo, P.
 - #1. Virtual Engineering Design in Aerospace Education and Research: Advanced Virtual Reality Simulation Tools Developed at RMIT University, Aerospace Engineering.
 - #2. Dynamics and Control of Towed Systems: Results of Research undertaken at RMIT University, Aerospace Engineering.
 - #3. Advances in 2D and 3D Co-Rotational Finite Element Method for Dynamic Modelling of Flexible Manoeuvring Structures: Results of the research undertaken at RMIT University, Aerospace Engineering on Aerodynamic Loading & Dynamics of Robotic Manipulator Arms.
 - Series of Invited Lectures at the University of Texas at Arlington, U.S.A.**, Monday 07- Wednesday 09 October 2002, Chaired by Director of MAIDO, Prof.G.S.Dulikravich;
 - ✦ Trivailo, P. Challenges of Non-Linear Dynamic Modelling in Aerospace Applications. (Overview of Dyanamic Research on Aerodynamic Loading and Dynamics and Control of Towed Systems, Undertaken at Aerospace Engineering, RMIT)-
Invited Lecture at the University of Newcastle, Wednesday, 03 July 2002, Chaired by ARC Federation Fellow, Prof.G.Goodwin;
 - ✦ Trivailo, P. Tether Applications for International Space Station Science Missions. -
Invited Presentation at the 2nd Australian Space Science Workshop/7th Australian Space Development Conference, National Space Society of Australia, Sydney, 15-17 July, 2002, Chaired by the President of the National Space Society of Australia, Philip Young;
 - ✦ Trivailo, P. Tether Technologies: New Horizons in Space Exploration (History, Successful and Unsuccessful Missions, Modern Concepts and Overview of Dynamics Research Projects on Tethered Satellite Systems Undertaken at RMIT University, Aerospace Engineering). - **Invited Lecture for the Royal Society of Victoria**, Australia, Thursday, 13 July 2000.
- Research results were presented at the Research Seminars/Conferences at the leading Research Centres and Universities overseas, including:
 - European Space and Technology Centre (ESTEC) in Noordwijk, ESA, The Netherlands;
 - Delft University, The Netherlands;
 - Centre Spatial de Liege, Belgium;
 - Katholieke University, Belgium;
 - Kingston University, UK;
 - Florida International University, USA;

- University of Texas at Arlington, USA;
- University of Maryland, USA;
- Howard University, USA;
- NASA Langley Res Centre (Structures Branch), USA;
- NASA Langley Res Centre (Control Branch), USA;
- Purdue University, USA;
- California Space Institute, University of California (San Diego), USA;
- Stanford University, USA;
- National Space Development Agency (NASDA), Japan;
- National Aerospace Research Laboratory (NAL), Japan;
- Tokyo Metropolitan Institute of Technology, Japan.

CURRENT AND PREVIOUS MAIN AREAS OF RESEARCH (FIELDS OF SPECIAL INTEREST):

- **Non-linear dynamic modelling of Tethered Space Systems:**
Real time simulation and control for the deployment/retrieval cases; real time simulation of tether severance, recapture, aerodynamic drag and interaction with the Earth's magnetic field, unscheduled situations in space including interaction with the International Space Station structural elements, interplanetary missions design, design of on-board systems for optimally controlled deployment/retrieval of tethered space systems.
- **Dynamic and Control of Towed Systems:**
Real time simulation and control of tethered systems for underwater [mine hunters] and aerial [aircraft with towed decoys, targets and probes, kite systems for energy generation using high altitude winds] applications. Precision deployment/retrieval of payloads, using smart towed systems.
- **Non-Linear Dynamic and Control of Spacecraft Formations:**
Use of fully nonlinear equations of motion to obtain periodic optimal trajectories for satellite formations (subject to multi-objective, multi-constraint optimisation) using direct transcription methods. This includes formation design, formation reconfiguration and formation deployment.
- **Smart structures, control systems design, vibrations, structural health monitoring and parameter identification in large flexible structures/systems:**
Smart structures; development of decentralized controllers for large flexible structures and robotic manipulator systems; development of new methods of damage/parameter detection in structures using vibration criteria.
- **Non-linear co-rotational FE modelling of elastic systems:**
Advanced dynamics modelling of reconfigurable space robots and structures undergoing large rotations and translations;
- **Nonlinear and linear aircraft flight dynamics, stability and automatic flight controls, Spacecraft Dynamics:**
Computer interactive simulation and 3D animation, Inverse problems, Orbital mechanics and optimisation.
- **Design of aircraft and space mechanisms:** theoretical and experimental investigation of space flywheels (mechanical accumulators of energy) and their protecting devices; design of new mechanisms, devices, and systems.

EXAMPLES OF MOST RECENT (2001-cur) RESEARCH GRANTS (FUNDED):

- **Non-Linear Dynamic Modeling, Optimal Design, Deployment and Control of Space Compound Systems (Multiple Cooperative Robotic Manipulators and Satellite Formations)** Australian Academy of Sciences (AAS) and Japanese Society for Promotion of Science (JSPS) 40-day Scientific Visit to Japan to undertake research on the Japanese Space Exploration Agency (JAXA) projects (August-September 2007).

Abstract:

An important goal of the project is to plan and prepare a set of research experiments onboard of the S-520 rocket. The annual launch of the Mission #25 is scheduled for August 2009 and is approved by JAXA. The work includes simulation of the deployment of the tape tether deployed for the scientific experiments from the S-520 rocket in space and experimental verification of the component sub-systems.

Another goal of the project is to develop a state-of-the-art technology for high-fidelity modeling, design and optimal cooperative control of compound space systems, working cooperatively under multiple constraints to complete complex missions in minimum time or with minimum energy expended. This generic methodology will be applied to two classes of systems: multiple flexible robotic manipulators and satellite formations in low Earth elliptic orbits.

Robotic manipulators are often required to work in cooperation with one another. This typically occurs in robotic assembly where more than one manipulator is required to reliably transfer a particular object from one location to another. Another example is a humanoid robot that must use its own arms to control the motion of a rigid object. This manipulation problem can be difficult to solve, particularly if it is to be performed optimally. In this proposal we aim to develop a generic method for solving these type of challenging optimal control problems within a computational framework called DIRECT (developed by Prof P.Trivailo's Group at RMIT), that discretizes the continuous optimal control problem via a Legendre pseudospectral method.

Another class of cooperative systems involves formation flying satellites, which promise to enhance the collection of scientific data from space. One challenging aspect of spacecraft formation flying is the design of periodic formations in elliptical orbits (station-keeping) and the deployment of such a formation. In this project a high-fidelity universal dynamics modelling numerical and control methodology of various satellite formations (including tetrahedral) in low Earth orbits, subject to multiple geometric constraints, will be developed. Furthermore, the same approach will be utilized for both geometry design and control design. This will be demonstrated by obtaining a minimum fuel transfer of the satellites from an initial configuration to the final tetrahedral formation in low Earth orbit. The distinct feature of the proposal is in utilizing completely non-linear equations and solving problem under numerous non-linear multiple constraints as a multi-objective optimisation problem, with Earth's oblateness and atmospheric drag taken into account.

- **Remote Delivery and Capture of Payloads using Aerial Deployed Tethers** (ARC Discovery Grant, funded by ARC; 2003-2004) – Research Team Leader & CI. Partner Investigator – Prof H.Fujii (Tokyo Metropolitan Institute of Technology, Japan).

Abstract:

The capability to rapidly transport payloads to and from remote locations is critical for search and rescue, disaster relief, remote communities, and military operations. Conventional technology is not well suited to this role, hence we propose to develop an intelligent system to manoeuvre a tether, towed from an aircraft, to pick-up or set-down a payload, with zero surface velocity. Because of the complex, nonlinear dynamics of a cable-body system, advanced modelling and nonlinear optimal control will be applied in this task. The resulting world-first system will provide important economic opportunities and demonstrate Australian scientific capacity for novel developing intelligent systems. The project doesn't only confine its work to fixed-wing aircraft – it is also developing intelligent tethered systems for ships, submarines and spacecraft. The research could one day improve sea rescue missions and the delivery of supplies to remote communities.

- **“Mach 5/50” Structural Multidisciplinary Design of Complex Systems** (***)Commercial-in-Confidence***) (funded by DSTO Australia and DARPA, USA; 2003-2004) – Research Team Leader & CI.

Abstract: The RMIT component of the Mach 5-50 project is on dynamics design of the advanced ballistic systems. It commenced in March 2003 with funding for one calendar year from the Australian Defence Science and Technology Organisation (DSTO) and DARPA (USA) under the leadership of Professor Pavel Trivailo.

The RMIT team was one of 4 groups working on this project in Australia. Other teams from Melbourne and Adelaide Universities, and from DSTO itself were tackling the same research tasks. In October 2003 the teams met in Adelaide to discuss their achievements. As a result the RMIT team was successful in attracting continuing funding for this project in 2004 and probably beyond, depending on the life of the project. The RMIT team was the only one to apply advanced 3D, dynamic, non-linear modeling approaches to the complex engineering design task. As the research problems and design strategies were refined, the RMIT team was then able to employ the shape optimization package ‘Reshape’ developed by Advea Engineering to meet the project design specifications.

Through the application of these advanced computational modeling and virtual engineering design approaches the RMIT team has been able to produce a world leading design meeting all the project specifications in less than one year. The RMIT design prototypes have been manufactured and successfully tested at DSTO facilities at Woomera in March 2004.

- **Dynamics and Control of Underwater Unmanned vehicles** (funded by Maritime Platforms Division, PSL, DSTO Australia and RIF; 2002-2003, 2003-2006, 2006-2007) – Research Team Leader & CI;

Abstract:

This research is to improve the effectiveness of Australia's \$6Billion Minehunter Fleet. Using advanced simulation and visualization, the Team developed advanced simulation, control and Virtual Reality visualization tools to help the operator of the underwater vehicle see and control what is happening underwater. This reduces their workload and improves mission success. DSTO has a research vessel known as the Wayamba that is to be used to test the visualization and control systems the Team developed. This is part of DSTO Australia's long term vision for an integrated marine platform with multi-mission capability.

- **Control of Reconfigurable Large Flexible Systems** (funded by VPAC; 2002) – Research Team Leader & CI;
- **Japanese Government PhD Exchange Scholarships Award-2002**, – Research Team Leader, together with Prof H.Fujii (Tokyo Metropolitan Institute of Technology, Japan).