EUR ING DR ALEX ELLERY

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Full Professor (Tenured) - **Canada Research Professor**

Centre for Self-Replication Research (CESER)

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General Areas of Interest – Space Robotics in its Broadest Context

- Space Manipulator Control for On-Orbit Satellite Servicing, Space Debris Mitigation and Extrasolar Planet Detection
- Planetary Rovers especially Rover Chassis Design, Traction Analysis & Autonomous Navigation/Path Planning
- Robotic Science Facility for Autonomous Rover Exploration & Roboticised Astrobiological Instrumentation
- Robotic Drilling & Mining in Extraterrestrial Environments
- Planetary Landers especially Micro-Penetrators
- Nano-Spacecraft Design especially Rover-On-A-Chip and 3D Printed Cubesats
- Artificial Intelligence through Hybrid Bayesian/Neural Nets for Spacecraft Autonomy and Cyber-Immunity
- In-Situ Resource Utilisation of Extraterrestrial Materials
- Extraterrestrial Manufacturing especially Additive Manufacturing
- Universal Construction and Self-Replicating Machines
- Biomimetic Approaches for Space Applications especially Brain Emulation and EDAC based on Biological Development
- Climate Change Mitigation using Solar Power Satellites and Solar Shields

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I. ACADEMIC QUALIFICATIONS

Duration	Award	Institution
Oct 1990 – Jun 1995	**PhD Astronautics & Space Engineering**	College of Aeronautics, **Cranfield Institute of Technology**, Bedfordshire, UK "Dynamics & control of a freeflying space robot with mounted manipulators for on-orbit satellite servicing"
Jun 1993 – Sep 1993	**Certificate in Space Studies**	**International Space University** (ISU) Summer School, University of Alabama, Huntsville, USA
Oct 1989 – Sep 1990	**MSc Astronomy**	Astronomy Centre, **University of Sussex**, Brighton, UK
Oct 1984 – Jul 1988	**BSc (Hons) Physics**	Department of Physics, **University of Ulster**, Northern Ireland, UK

II. PROFESSIONAL INSTITUTION MEMBERSHIPS

Grade	Institution	Entry Membership Election Year
Licenced (**P.Eng** – Engineering Physics)	Professional Engineer Ontario	2018
Fellow	Royal Society of Biology	2019
Fellow	British Computer Society	2019
Fellow	Institution of Mechanical Engineers	2015
Fellow (**C.Math**)	Institute of Mathematics & its Applications	2003
Fellow (**C.Eng/Eur Ing/C.Mgr**)	Institution of Engineering & Technology	1998
Fellow (**C.Phys**)	Institute of Physics	1995
Fellow	Royal Aeronautical Society	1993
Fellow	British Interplanetary Society	1993
Fellow	Royal Astronomical Society	1991

Fellowship is the highest grade of professional membership and requires demonstrable evidence of significant contributions to the field of expertise.

III. PROFESSIONAL EXPERIENCE

Duration	Position	Institution
Jan 2007 - present	Full Professor (2018) (Tenured) – **Canada Research Professor** (Canada Research Chair in Space Robotics & Space	Department of Mechanical & Aerospace Engineering, **Carleton University**, Ottawa, Canada Head of Centre for Self-Replication Research (CESER)

	Technology 2007-2017)	
Apr 2004 – Dec 2006	Lecturer in Spacecraft Engineering	Surrey Space Centre, School of Electronics & Physical Sciences, **University of Surrey**, Guildford, UK Head of Robotics Research Group
Aug 2001 – Apr 2004	Senior Lecturer in Spacecraft Engineering	School of Engineering, **Kingston University**, London, UK
Sept 2000 – Jul 2001	Project Manager of Herschel Space Observatory & Planck Space Telescope instrument groups	Astrophysics Laboratory, Queen Mary College, **University of London**, London, UK
Jul 1997 – Aug 2000	Software Engineer (Consultant)	Space Division, **Logica UK Ltd**, London, UK
Jan 1996 – Jun 1997	Senior Clinical Scientist (Neurotology)	Department of Neurotology, **Royal National Throat Nose & Ear Hospital**, Greys Inn Rd, London, UK
Oct 1988 – Sep 1989	Systems Design Engineer	**Vickers Shipbuilding & Engineering Ltd** (VSEL), Barrow-in-Furness, UK

IV. EVIDENCE OF ESTEEM

AWARDS

- **Canada Resarch Professor (**since 2017)
- **Canada Research Chair** in Space Robotics & Space Technology (2007-2017), a prestigious Canadian award recognising leadership in academic research
- **Donald Michie Trophy** from British Computer Society for a paper entitled “Practical limits to transfer learning of neural network controllers from Earth to space environments” *Proc 42nd SGAI Int Conf on Artificial Intelligence* **-** *Lecture Notes in Artificial Intelligence* **13652**, 3-16 (2022)
- **5th Best Paper Prize** at 23rd World Energy Congress (WEC), Istanbul, Turkey (2016) awarded by World Energy Council (WEC was attended by Vladimir Putin of Russia and Tayyip Erdogan of Turkey)
- Best papers of sessions of International Astronautics Congress (IAC) for 2015 (one paper) and 2017 (two papers)
- **George Stephenson Medal** and William Sweet Smith prize from Institution of Mechanical Engineers (2005) for a paper entitled “An engineering approach to the dynamic control of space robotic on-orbit servicers” *Proc Inst Mechanical Engineers Part G: J Aerospace Engineering* Vol 218, 79-98 (2004)

Figure 1. Andrew Ives, President of IMechE (2005) ***left*****, presents Dr Alex Ellery** ***right*** **with the Stephenson medal [from Agenda vol 4 (8), page 2]**

RECENT INVITED TALKS

- Invited speaker "Sustainable ISRU" Space Resources Week Luxembourg 2022 and 2023 (V)
- Invited speaker "Lunar resource manufacture SPS – how much is feasible?" 1st ESA Space-based Solar Power for Net Zero Workshop 2021 (V)
- Invited speaker to NASA Space Portal Commercial Space Lecture series (Jun 2021) "Self-replicating machines are the only means through which to spread through the solar system"
- Invited speaker at NASA Space Apps Toronto – "Are self replicating machines a technology of today or tomorrow?" Oct 2021
- Invited speaker for 1st Greek Space Science & Technology Conference (May 2021)
- Invited speaker for IMechE North American branch "Building self-replicating machines to colonise the Moon" (Mar 2021)
- Invited speaker for Canada SEDS conf (Ascension) on on self-replicating machines (Feb 2021)
- Invited keynote speaker for GECCO (Genetic & Evolutionary Computation Conference) 2020 "Information return on investment condition in self-replicating machines" (Jul 2020)
- Invited speaker at Lunar In-Situ Resources Utilisation Workshop, ESTEC (3-5 Jul 2018)
- Invited speaker for 20-minute Pint of Science talk Ottawa (15 May 2018)
- Invited speaker to NASA Jet Propulsion Laboratory on "Building a Self-Replicating machine Ex Nihilo on the Moon" (Nov 2017)
- Invited speaker for SEDS Canada, Flight Research Lab, NRC, Ottawa (26 July 2017)
- Invited speaker at the 12th Military Space Situational Awareness Summit London UK on "Artificially intelligent spacecraft as a defence strategy against hostile cyber-intervention" (26-27 Apr 2017) - http://www.smi-online.co.uk/milspace2017-docs.asp
- Invited speaker (2014 and 2015) in additive manufacturing for the RAPID Canada Conference day of the Canadian Manufacturing Technology Show, Mississauga, ON
- Présenter at Lunar ISRU Workshop 2019, Lunar & Planetary Institute, Columbia, MD

EDITORIAL ROLES

- Editorial board (associate editor) of the *International Journal of Astrobiology* (2002-2015) and (2019-current)
- Editorial board of *Frontiers in Space Technology* (2022) - *J Field Robotics* (2022-current) and (2006-2010) - *Int J Advanced Robotic Systems* (2004-2006)
- Guest editor for special issue on von Neumann Probes for *International Journal of Astrobiology*
- Guest editor for special issue on Biomimetic Design & Techniques for Space Applications for the journal *Biomimetics* (2019)
- Guest editor for special issue on Space Robotics for journal *Robotics* (2019)

- Guest editor for special issue on Robotic Astrobiology for *International Journal of Astrobiology* (2017)
- Guest editor for a special issue on Space Robotics for *International Journal of Advanced Robotic Systems* (2014)
- Editorial board for Praxis Publisher's Astronomy & Space Science Series reviewing proposed space-related book titles (2003-2007)
- Co-editor (with Ulrich Nehmzow, Chris Melhuish, Mark Witkowski and Eddie Moxey) of the *Robotics & Autonomous Systems* journal special issue Towards Autonomous Robotic Systems (2007) vol 55 (9)

REVIEWING ACTIVITIES

- External reviewer for University of Western Ontario's Professional Masters course in Space Studies (2021)
- Reviewer for NASA's Postdoctoral Program (NPP) on astrobiology instrumentation especially rover-deployed Raman spectroscopy (2012-2017)
- Expert Evaluator in Space Robotics (a European strategic space technology) for the European Commission Horizon 2020 programme grant applications (2016, 2018, 2020 and 2022)
- Mitacs research institute College of Reviewers; I have been a regular reviewer for NSERC grants and Canada Research Chair applications
- Reviewer for the *ASCE Earth & Space Conference, Int Symp Artificial Intelligence, Robotics & Automation in Space (iSAIRAS), IEEE International Conference on Robotics & Automation (ICRA)* and *IEEE Int Conf Automation Science & Engineering (CASE)*; Review committee for the *Towards Autonomous Robotic Systems (TAROS)* annual conference (annual UK mobile robotics conference) for 2006-2010
- Reviewer for several journals in space engineering, space science, robotics, biomimetics and astrobiology - *Planetary & Space Sciences, Advances in Space Research, Aeronautical Journal, Robotics & Autonomous Systems, International Journal Advanced Robotic Systems, Control Engineering Practice, International Journal of Astrobiology, Journal of Field Robotics, Bioinspiration & Biomimetics, Acta Astronautica, Journal British Interplanetary Society* journals.

CONFERENCE ORGANISATION

- Conference co-chair for 8th Interstellar Symposium, McGill University, Montreal (Jul 2023)
- Programme committee for special session on *Biologically Inspired Robotics at Adaptation in Intelligent Systems & Biology (AISB) Conference*, University of Bristol (2006)
- Host and conference co-chair for the annual UK Robotics conference TAROS (*Towards Autonomous Robotic Systems*) at the University of Surrey in August 2006
- Host and conference organiser for a two-day symposium at University of Surrey in 2005 on "Low-cost robotic planetary exploration: a UK vision" under the auspices of the Space & Planetary Robotics Network to showcase UK research activities in this area to invitees from UK industry, ESA representatives, and research council representatives
- I have presented at number of conferences which publish extended abstracts rather than full papers including European Geophysical Society Conference (2003) Nice France, 4th European Mars Conference (2004) Milton Keynes UK, Space Resources Roundtable/Planetary & Terrestrial Mining Sciences Symposium (2015, 2017 and 2021) Montreal Canada, Our Common Future Under Climate Change (2015) Paris France, European Astrobiology Network Association Conference (2016) Athens Greece, COSPAR (2022) virtual presentations - "In-situ resource utilisation – a sustainable approach to stewardship of the Moon" and "Could they have been in the asteroid belt? The subtleties of technosignatures"

- I have chaired numerous sessions at space, robotics, space robotics and biomimetics/astrobiology conferences

MEMBERSHIP OF CONSORTIA/ACADEMIC PARTNERSHIPS

- Member of scientific board of the Canadian Space Mining Corporation (2018-2022)
- Member of academic board for the NASA Lunar University (since 2020)
- Member of American Society of Civil Engineers (ASCE) Regolith Operation Mobility & Robotics Technical Committee (2016-2018)
- Canadian RESOLVE (subsequently Lunar Resource Prospector) science definition team (2013) representing the Canadian science contribution to the NASA RPM mission until Canadian contribution cancelled (2015) followed by mission cancellation (2017)
- Collaborator on the NSERC CREATE team on TEPS (Technologies for Exo-Planetary Science) led by York University and the NSERC CREATE team on CATP (Canadian Astrobiology Training Programme) led by McGill University (ended in 2015)
- Chair of Canadian Micro-Penetrator Consortium (2011-2019) following my hosting a two-day workshop on Micro-Penetrators at the Canadian Space Agency
- Member of the Canadian Astrobiology Working Group - I was the astrobiology discipline co-chair on the Steering Committee at the (1-3 Dec 2008) Proc 6th Canadian Space Exploration Workshop (CSEW6) and was the primary author of the astrobiology section to the CSA's Canadian Scientific Priorities for the Global Exploration Strategy (2009) and subsequently championed micro-penetrators for astrobiological exploration of Enceladus/Europa at CSEW 2016 with Prof Lyle White at McGill.
- Former Chairman of the Astrobiology Society of Britain for 2005/2006 which is affiliated to the International Astrobiology Network led by NASA Institute of Astrobiology
- Co-founder of UK Penetrator Consortium (2003) which has developed the only European micro-penetrator led my Mullard Space Science Laboratory
- Co-founder and deputy chair of UK Space & Planetary Robotics Network (SPRN) in 2002-2006
- Steering committee of the UK BiroNet (Biomimetic Robotics Network) in 2005/2006
- Co-ordinator of EPSRC TREATAE (Transfer of Engineering & Analytical Technology to Astrobiological Exploration) Network activities in Sampling on Planetary Surfaces in 2004-2006
- Member of SALE (Subsurface Antarctic Lake Ellsworth) drilling consortium until 2007 on emigrating to Canada

EXTRACURRICULAR TEACHING

- International Space University (ISU) staff co-chair (2007) for DOCTOR (developing on-orbit servicing concepts, technology options and roadmap) design project and lecturer (2014) in Space Robotics to the ISU summer school, Beijing, China and Montreal, Canada respectively - I hold an adjunct professorship at ISU. From 2010-2014, I served on the Canadian Foundation for the ISU which selects Canadian candidates for the two ISU academic programmes
- Invited two-day course lecturer on On-Orbit Servicing at the University of Delft Master of Space Systems Engineering (SpaceTech**)** course in Lindau Germany (2006) for international leaders in space business

V. CONSULTANCIES

Task	Client	Duration	Contract award
Autonomous Spacecraft Planning using Hybrid Neural Networks	DRDC	2018-2019	$25,000
Expert Evaluator (Space Robotics)	EU	2016, 2018, 2020 and 2022	$15,000 x 4
Lunar Resource Prospector Mission (RPM) science proposal definition	CSA	2014-2015	$25,000
Micro-Penetrator Feasibility & Concepts Analysis	CSA	2012-2013	$25,000
Lunar Origins & Resources Experiment (LORE)	MPB Montreal	2010-2011	$25,000
Autonomous Navigation and Traction Analysis (LEMUR – lunar exploration manned utility rover)	MacDonald Dettwiler Associates (MDA), Brampton	2008-2009	$15,000
On-orbit servicing – the way forward	DLR Oberfaffenhoffen, Germany	2003-2004	€15,000

VI. RESEARCH GRANTS

Total Integrated Research Grant Awards: $4.268 M

Grants awarded at Carleton University

Project	Awarding/Collaborating Body	Award Duration	Grant Award Allocated
CREATE Additive Manufacturing (led by York University)	NSERC	2021-2026	$15,000.y for 5 y = $75,000
Open Space Innovation Award	ESA	2020-2024	$51,000
Space Debris Identification (led by Magellan)	CSA	2022-present as PI	$25,000
Lunar Micro-Penetrator (led by Magellan)	CSA	2019-2021 as PI	$40,000
Enceladus Micro-Penetrator Study (led by Magellan)	CSA	2018-2019 (1 year) as PI	$25,000
MICRO-LIFE (FAST) extension	CSA	2020-2022 (3 years)	$100,000

MICRO-LIFE (FAST) astrobiology instrumentation	CSA	2017-2020 (3 years) as coPI (current)	$370,500
In-Situ Resource Utilisation	NSERC	4 months (summer annually 2013-2017) as PI	$5000/y per student x 2 = $40,000
Self-Replicating 3D Printer	MITACS	3 months (summer annually since 2014) as PI	$15,000/y x 10 years = $150,000
Robotic Astrobiology	NSERC Discovery (current)	2016 as PI	$25,000 x 6 years = $150,000
Rover Path Planning	NSERC Engage/Neptec	2012 (6 months) as PI	$25,000
Canadian Astrobiology Training Program	NSERC CREATE	2012-2016 as coI	$25,000 x 4 years = $100,000
Probabilistic Vision	ESA	2012 (4 months) as PI	$42,000
Mars Methane Analogue Mission	CSA	2011 (1.5 years) as coPI	$52,000
Scent of Science: Autonomous Source Localisation	ESA	2011-2012 (4 months) as PI	$42,000
MITACS	MPB Montreal	2011-2012 as PI	$55,000
Mars Yard infrastructure award	Carleton University	2011 as PI (lump)	$30,000
Kapvik Micro-Rover Development	CSA	2010 (2 years) as PI	$330,000
Lunar Dust Experiment	MPB/CSA	2009 (1.5 years) as coPI	$16,000
Bio-inspired robot control	NSERC Discovery	2010 as PI	$22,000 x 5 years = $110,000
LORE instrument	MPB/CSA	2009 (2 years) as coI	$30,000
Bio-inspired space robot control	NSERC Discovery	2007 as PI	$18,000 x 2 years = $36,000
Robotics laboratory infrastructure	CFI-Ontario Provincial Government	2008 (lump) as PI	$443,630
CRC support	OVP Carleton University	2007 as PI	$35,000 x 3 years = $105,000
Startup fund	OVP Carleton University	2007 (lump) as PI	$30,000 (lump)
Canada Research Chair	Government of Cabada	2007-2017	$100,000 x 10 years = $1 M
TOTAL			**$3.473 M**

Grants awarded in UK

Project	**Awarding Body**	**Co-Investigators**	**Duration**	**Allocated Award Total**
ExoMars optic	PPARC (UK)	EADS Astrium UK	2006 (6	₤15,000

flow-based navigation feasibility study (PI)		(lead), Surrey Space Centre	months) as PI	
Rover chassis evaluation tool (coI)	European Space Agency (ESA)	Contraves Space Switzerland (lead), Surrey Space Centre, DLR Germany, EPFL Switzerland	2004-2006 (3 years) as coPI	€78,000
Bionics and space systems design (PI)	ESA	Surrey Space Centre (lead), University of Bath, University of Sussex, Open University, EADS Astrium UK	2003-2004 (1 year) as PI	€150,000
ExoMars rover and Pasteur payload Phase A study	ESA	EADS Astrium UK (lead), Surrey Space Centre UK, DLR, von Hoerner & Sulger GmbH, EPFL Switzerland, LAAS France	2004 (1 year) as coI	₤30,000
Elastic loop mobility system study	ESA	Kingston University	2002 (4 months) as PI	€28,000
Mars entry descent and landing systems	EPSRC/SSTL	Kingston University/University of Surrey	2002-2005 (3 years) as PI	₤60,000
Robotic vehicle traction experiment	SRIF	Kingston University	2004 (lump) as PI	₤30,000
TOTAL				**₤360K**

VII. TEACHING DEVELOPMENT

One of the earliest lessons I had in teaching was the Balancing Studies course at Kingston University, an ill-conceived final year course for all engineering students across the school (around 150 students). It was designed to plug any gaps in engineering students' knowledge by teaching essentially remedial physics to every type of 4th year engineering student in the faculty – mechanical, electrical/electronic, control, aerospace, and production engineering. It was ill-conceived because it was too late to teach these topics to too diverse a group. The first year I taught it, it was an unmitigated disaster – discipline was difficult to enforce, students were bored and unmotivated, and I didn't know why I was teaching this course as it served no useful function. I wrestled with trying to figure out what I could teach final year engineers near the end of their studies that might be useful to them in their future careers. The following year, I decided to teach critical thinking through the scientific method using a socratic approach covering topics as diverse as myths, spiritual worlds, deities, psychic phenomena and extraterrestrial intelligence in the context of belief versus the power of physical evidence. It was a fanatastic success. I was told by several students that it was the most rewarding and fascinating course they had sat at Kingston. The lesson? Students must be engaged to learn. I have tried to introduce the three rhythms of education into my lecture courses as espoused in Alfred North Whitehead‘s *Aims of Education* (1926) – a sense of wonder (what he referred to as “romance”), disciplined rigour (which he referred to as “precision”), and application of knowledge (which he referred to as “generalization”).

I have taught a range of courses from foundation to master’s level throughout my academic career. They have focussed primarily on spacecraft engineering and robotics, though they have also included more generic courses such as electronics, control and instrumentation (mostly as a result of teaching in mechanical engineering departments where such subjects are typically assigned to roboticists!). I have also taught robotics from a mechanical perspective (my robotics courses have concentrated on manipulator kinematics, dynamics, trajectory interpolation and control). According to the historian Geoffrey Elton in *The Practice of History* (1967), "The university must train the mind, not fill the untrained mind with multi-coloured information and undigested ideas, and only the proper study of an identifiable discipline according to the rules and practices of that discipline can accomplish that fundamental purpose." He was wrong (or as physicists like to retort with the ultimate insult: not even wrong). In my view, a major part of the job of an engineer is to convert undigested ideas into practical solutions. As a roboticist, I am highly critical of the notion that mechanical and electronic engineering are separate disciplines and never the twain shall meet – roboticists cannot afford to pigeon-hole their mentality in this fashion. Furthermore, given the systems aspects of today’s complex engineering, engineers must be cross-trained and equipped with skills in mechanical, electronic, control and software engineering (sometimes called mechatronics) - today, vehicles like aeroplanes or spacecraft are built around their avionics. Furthermore, engineers must be versed in instrumentation in order to devise and build experimental apparatus. The demarcation attitude, promulgated by the likes of PEO which enforces separation of mechanical and electronic engineering, is destructive and regressive (much like the PEO’s insistence that design is separable from analysis in engineering – analysis without design is physics and design without analysis is landscape gardening!).

I believe in the primacy of the lecture as the teaching tool of choice – the use of ICT/media can be valuable but not shoe-horned into a programme for its own sake. I do not believe that MOOCS will replace the traditional lecture (as evidenced by their high drop-out rates) as social interaction is a major contributor to the effectiveness of lectures – Alfred North Whitehead similarly stressed the value of the social dimension of communal learning with one’s peers. This has been reinforced by the COVID experience of online lecture delivery as deficient. There is a theory that all academic engineers should be able to teach all aspects of the first two years of an engineering degree. This may well be so, but it misses the point. Inevitably, lectures taught by academic engineers with expertise in that subject will always be richer, deeper, more challenging and insightful than those without. There is also a theory that all courses should be “standardised” to ensure that any graduate lecturer can teach them from standardised course material. This is an utter nonsense as well as a recipe for student boredom – students might as well be given the assigned text and work through it themselves. The value of the university lecturer – indeed, the *only* value of the university lecturer – lies in his/her personal experience and expertise and how it can enlighten the subject at hand and be delivered in an instructive manner. I use anecdotal examples all the time in my lectures and the students usually respond to that. I use every opportunity to introduce my own research into my lectures to inject freshness and relevance into them. I have almost 100% student attendance in all my lectures.

Due to my primary training as a spacecraft engineer, I have taught all aspects of spacecraft engineering including orbit mechanics and attitude dynamics as well as spacecraft bus and payload systems (rather curiously, orbital mechanics and attitude dynamics are not requirements for space engineering qualification according to PEO yet cartography is!). Space technology is one of the “Eight Great Technologies” (David Willetts MP, Policy Exchange, London, 2013). I have taught space engineering courses in three universities across two continents including graduate courses. I believe this has given me some insight into how such courses should be developed. My spacecraft engineering courses are given from the perspective of designing a spacecraft within the constraints of mass, propellant, power and data budgets and how those budgets require detailed analysis to feed into the design. All design decisions must be analysed as early as possible to prevent mass creep, the bane of the spacecraft engineer. I have written several textbooks to support my teaching as my experience has been that most textbooks either do not exist (such as my *Introduction to Space Robotics* and *Planetary Rovers* books) or do not offer the spectrum of skills I believe is necessary for a space engineer (my unpublished *Space Technology for Astrobiology Missions*). For instance, electronics in most space engineering textbooks is weak or non-existent, almost certainly the result of space engineering evolving from aerospace engineering capabilities in mechanical engineering departments. This is unsustainable – modern vehicles, be they aircraft or spacecraft, are ever more reliant on avionics (to wit, the vast expansion of drones in military and civil applications and the advent of autonomous vehicles about to traverse our roads).

Whilst at the University of Surrey, I was involved in the introduction of a remarkable teaching tool that I used in my teaching labs to support my spacecraft engineering courses – the EyasSAT nanospacecraft model spacecraft developed at the US Air Force Academy [Barnhart D, Vladimirova T, Ellery A, Lappas V, Sweeting M (2006) “Utilising the EyasSAT concept in space systems engineering courses at the University of Surrey“ *International Astronautics Congress*, Valencia, Spain, IAC-06-E1.4.04]. I proposed this teaching tool to Carleton University where it has been an unprecedented success as one of the defining features of Carleton University’s B.Eng in Aerospace Engineering with Space Systems course. We have 12 EyesSAT stations in our undergraduate space engineering lab. The value of practical hands-on training is difficult to over-state – computer simulation and theory are no substitutes for developing practical engineering acumen, a philosophy that I practice through the extensive assignment of projects in my courses. I am a great believer that all engineering students should have the opportunity to manufacture things using traditional and non-traditional tools, especially with the ready availability of 3D printers. Student response to such opportunities are almost universally positive (though there are always dissenters disinterested in such opportunities).

One of the most important duties to which we as university professors are bound is the maintenance of professional standards. In many respects, this is contrary to another duty that is the treatment of students as customers who are paying for a product (the award of a degree). I regard my duty to the profession as a higher duty than that to assuage the baser obligations of commercial interests. There are three types of student – industrious with flexible thinking (who make good engineers) – industrious but procedurally-oriented (who make good technicians) – and the indolent (and the worst variant thereof, the barrack room lawyer). The latter I do not tolerate especially in fourth year when students are about to embark on a profession in which idleness equates to irresponsibility and, potentially, negligence of which surely the iron ring is meant to be a reminder (I was greatly privileged to be asked to give a student his ring during the ring ceremony). The technician mentality also tends to struggle with my teaching style which emphasises breaking the comfortable bounds of spoon-feeding to which students have become accustomed – I believe, in the fourth year, that expanding students’ exposure to open problems, allows them to explore and understand the constraints of time and effort within the bounds of their own abilities (for many, this exploration of their abilities is a revelation to them). Furthermore, in my lectures, I provide extensive material and emphasise the most salient topics.

Of course, not all students respond well to this – some want formulae and to work through example problems *ad infinitum* without having to exercise much thought. Their goal is passing exams but education is not just about passing exams. As evidence of the efficacy of my approach, I frequently have several students wishing to work in my lab during the summer or to do directed studies under my supervision – I look for enthusiasm with hands-on capabilities (evidenced by their project assignments) rather than academic prowess (in my opinion, a rarer skill). Several of them have gone onto graduate studies (not necessarily with me or at Carleton – two of my MASc students are now at JPL after PhDs from other institutions. I constantly have enquiries about directed studies under my supervision and volunteers to work in my lab over the summer for abysmal pay. One MITACS (visiting) student from Tunisia wrote in an email to me: "Hello Professor Alex, I want to thank you another time for the opportunity of working on such an interesting project with very helpful and kind teammates and in a very modern lab, and especially under the supervision of a well known and respected professor of your level. I was always willing to work on futuristic projects and innovative ideas, that was my main reason for choosing your project. And even though I didn't achieve all the objectives we were trying to reach, I am still very proud to be part of such an interesting project and happy for the work done so far…. ".

As recommended in *Educating the Engineer of 2020: Adapting Engineering Education to the New Century* (2005) by the US National Academy of Engineering, I place great store on interdisciplinary individual design projects and including real world case studies within my courses. For their assessed assignments, I do not give students project ideas but ask them to propose a relevant project of their own choice within a fluid definition of the course's scope – initially, this scares students as they are not used to such freedoms. These fears are exacerbated because the terms of reference I provide are deliberately vague beyond the guideline that it should impress me. By opening the scope, students can pursue something that interests them. By not imposing specific controls, I am not artificially imposing limits on their exploration – this is a characteristic of planetary missions where there are so many unknowns and little or no previous human experience. I find that I get the best out of most students this way (the enthusiastic ones anyway). The most important thing they learn is building confidence in their competence as engineers and exercising their ingenuity as engineers. I have seen some amazing project results – all students who have attended my courses reckon they mature in my courses as engineers even if they have not performed particularly well. I have encouraged my undergraduate students to build payload instruments themselves (as part of a space instrumentation course I teach) – the most remarkable instrument was built by a RCAF officer cadet undergraduate who constructed a working Raman spectrometer (for which I re-imbursed him at $2000 – a bargain when even a low-end Raman spectrometer costs upward of $12,000). Similarly, for my vehicles course (based on planetary rovers), I have seen some diverse and fascinating constructions including two ion engines (which I also have kept) and, most impressively, a working coilgun. Of course, this approach works most effectively in final year and graduate courses and would not be suitable for earlier years of undergraduate teaching.

I take the view that engineers are problem-solvers despite their specific training, be it as a mechanical, electrical or any other type of engineer. We are faced with some of the greatest challenges that confront our species. As engineers, we must rise to this challenge, for it is from engineers that solutions will emerge – there is no other profession fit for this task. We cannot afford to tackle these problems piecemeal – to use a hackneyed political term that so rarely characterises political ideas, it requires "joined-up" thinking. We must be grooming the next generation of engineers to be capable of tackling the big problems that will face their society and for this they will require broad as well as deep engineering knowledge.

Carleton University Courses Taught:

Course	Level	Semester	Period
Space Robotics	Graduate	Winter	2021-present
Spacecraft Design II (Payloads)	4th year	Fall	2010-present
Vehicle Engineering II	4th year	Winter	2010-present
Orbit Mechanics	3rd year	Fall	2019
Spacecraft Design Lab	3rd/4th year	Fall	2007-2011
Spacecraft Design I (Space Systems)	3rd year	Fall	2009-2011 and 2017
Space Robotics	Graduate	Winter	2007-2010
Spacecraft Design	4th year	Fall	2007-2009
Measurement & Data Systems	4th year	Winter	2007
Spacecraft Design Project*	4th year	Fall and Winter	2007-2011 and 2017-present

* For 3 years, I was the lead engineer for the 4th year capstone spacecraft project based on my proposal – a lunar micro-penetrator design with an emphasis on physical prototyping

University of Surrey Courses Taught**:

Space Robotics	Graduate	Spring	2004-2006
Space Mission Design	3rd year	Winter	2004-2006
Electronics Laboratory	2nd year	Winter and Spring	2004-2006
Multidisciplinary Design Project	4th year	Winter and Spring	2005-2006
Tutorials	1st and 2nd year	Winter and Spring	2004-2006

**at Surrey University, I had a custodial role to several 1st and 2nd year undergraduates

Kingston University Courses Taught***:

Robotics Engineering	Graduate	Winter	2001-2004
Electronics & Control Engineering	2nd year	Spring	2002-2003
Introduction to Astronautics	3rd year	Winter	2001-2004
Space Vehicle Design	4th year	Winter	2003-2004
Space Applications	4th year	Spring	2003-2004
Mechatronics	4th year	Spring	2001-2002
Balancing Studies	4th year	Winter	2001-2003
Technology Mathematics I	1st year	Spring	2001-2002

*** I developed the syllabus for a 4th year module "Nanotechnology" for the course catalogue

QMC University of London Courses Taught:

Electromagnetism Tutorial	1st year	Winter	2000

Supervision of Graduate Students:

Name	Graduate level****	Start	Funding source	Thesis topic
Alex Gmerek	MASc	Jan 2022	NSERC Discovery	Planetary instrumentation (TDLAS)
Anchal Gupta	MASc	Sep 2022	Self-funded	RatSLAM for lunar rovers
Amin Motahari	MASc	Sep 2021	Self-funded	Orbital manufacturing facility
Xavier Wall	PhD	Sep 2021	NSERC CREATE	Lunar FFC process/aluminium 3D printing facility
Bertrand	MASc	Jan	RCAF	Chemical pre-processing of lunar

Thibodeau (with Prof Brian Cousens)		2021		anorthite
Rohit Gaikwand	MASc	Jan 2021	Scholarship	Development of in-house multi-headed 3D printer
Benjamin Segobaetso (current)	PhD	Jan 2020	Dep of Philosophy	Ethics of lunar colonisation (co-supervision with Prof Gordon Davis and Prof Jim Davies)
Satinder Shergill	PhD – one year placement from Cranfield University UK	Jan 2020	Cranfield University	Comminution and beneficiation of anorthite (co-supervision with Dr Jenny Kingston)
Yue Sun	PhD - one year placement from Harbin Institute of Technology China (awarded)	Feb 2018	HIT China	Bio-inspired plume tracking delta-v trajectories for an Enceladus penetrator
Shubhank Sondhiya	MASc (awarded)	Sep 2018	CSA	Robotic molecular biologist for planetary exploration
Nidhi Kamra (current)	MASc	Jan 2020	P/T	Analogue neural network with backpropagation circuitry
Collins Ogundipe (current)	PhD	Jan 2018	Nigerian Space Agency	Multi-layer control of on-orbit servicing manipulators for robust grappling and ORU exchange
Alex Tettenborn (current)	PhD	Jan 2016	RA	Autonomous rock recognition using Gabor filtering
Abdurr Elaskri	MASc (awarded)	Sep 2015-Aug 2021	Libyan scholarship fund	3D printing of mechatronic components
Elizabeth Banken	MSc – one year placement from Rhine-Waal University of Applied Sciences (awarded)	Jan 2019	RWUAS	Lunar hydroponic greenhouse productivity study (co-supervision with Prof William Megill)
Adam Vigneron	MASc (awarded)	Sep 2011	Bristol Aerospace	HEO navigation and attitude reference control (co-supervision with Prof Anton de Ruiter)
Jordan Ross	PhD (transferred to Dalhousie Uni in year 2)	Sep 2014	RA	Manipulator control for on-orbit servicing using feedforward modelling
Pablo Molina	MASc (awarded)	Sep 2012	RA	Rover 3D SLAM using streovision and velocimetry
Jordan Ross	MASc (awarded)	Apr 2012	RA	Automated rover camera control using forward predictive control
Yingying Ye	MASc	Apr	RA	Rover reactive navigation using

	(awarded)	2012		evolved neural networks
Cameron Frazier (with Prof Natalie Baddour)	MASc (awarded)	Jan 2012	RA	Rover path planning using tailored potential fields
Chris Nicol (with Prof Ed Cloutis)	MASc (awarded)	Sep 2011	NSERC CREATE	Mars methane plume tracing using biomimetic approaches
Helia Sharif (with Prof Claire Samson)	MASc (awarded)	Jan 2010	RA	Automatic geological classification of rocks using Bayesian nets
Matt Cross	MASc (awarded)	Jan 2010	CSA	Rover motor control and automated traction control with soil parameter extraction
Rob Hewitt (with Prof Anton de Ruiter)	MASc (awarded)	Sep 2009	CSA	Rover fastSLAM for autonomous navigation by LIDAR
Tim Setterfield	MASc (awarded)	Sep 2009	CSA	Rover chassis characterisation and automated traction control
Marc Gallant (with Prof Josh Marshall)	MASc (awarded)	Sep 2009	CSA	Rover path re-planning with science target recognition
Robert Scott	PhD (awarded)	Jan 2008	DRDC	Kalman filtering to track on orbit servicing spacecraft
Brian Lynch (with Prof Fred Nitzsche)	PhD (awarded)	Sep 2007	CSA	Shape memory alloy actuators for robotic manipulators
Mark Swartz	MASc (awarded)	Sep 2007	RA	Neural network-augmented Kalman filters for Mars rover slip estimation
Adam Mack (with Prof Bruce Burlton)	MASc (awarded)	Sep 2007	Bristol Aerospace	Onboard satellite operations autonomy
Gregory Scott	PhD – awarded 2010 (Surrey)	Oct 2003	EPSRC	Traction analysis for legged rovers
Elie Allouis	PhD - awarded 2006 (Surrey)	Oct 2003	EPSRC CASE	Entry descent and landing systems for Mars
Nildeep Patel	PhD - awarded 2005 (Surrey)	Jan 2002	EPSRC	Mobility analysis for Mars rovers
TOTAL COMPLETED	5 x PhD + 16 x MASc			

****Canadian MASc is a two year research degree

Supervision of Post-Doctoral Research Fellows (PDRF)

Name	Duration	Institution	Role
Dr Brian Lynch	2017-2018	Carleton University	PDRF in sampling drill development
Dr Brian Lynch	2013-2014	Carleton University	PDRF in in-situ resources utilisation research

Dr Ala Qadi	2010-2012	Carleton University	PDRF on Kapvik project
Dr Yang Gao (now Prof)	2004-2006	University of Surrey	PDRF in biomimetics research
Dr Mini Saaj (now Prof)	2004-2006	University of Surrey	PDRF in rover traction research

Mentoring of Assistant Professors

Name	Duration	Institution	Role
Prof Josh Marshall	2008-2010	Carleton University	Joint supervision of MASc projects
Prof Anton de Ruiter	2011-2013	Carleton University	Joint supervision of MASc projects

VIII. ADMINISTRATIVE DUTIES

In the UK, the general day-to-day administrative load was more taxing than in Canada due to the centralisation of university administration following Parkinson's Law [C Northcote Parkinson (1957) "Parkinson's Law and other studies in administration" *Ballantine Books*, New York]. Canadian universities are spared the more irksome burdens of continuous quality assurance, research reviews, teaching reviews, examination auditing, etc. However, there is the five year accreditation review by Professional Engineer Ontario for which I am partially responsible for some of the course content and standards in the B.Eng in Aerospace Engineering stream D (space systems design). I contributed to the design of this stream and have delivered the core courses for it which came on-stream two years after I was hired. In particular, I reviewed all the major North American space engineering courses comparing them to my own experiences at the University of Surrey, Kingston University, Cranfield University and the International Space University. Indeed, I was hired at both Kingston University and University of Surrey for new space engineering courses and had contributed to their design. However, as with all things, the constraints imposed by the degree structure at Carleton (a fixed year 1 and year 2 syllabi) limited flexibility necessitating compromises. The students in Aerospace Engineering essentially experience no aerospace flavour until year 3. However, I believe that the stream D course is comparable to the best anywhere. At Carleton, whilst a Canada Research Chair (CRC), my recent administrative load was relatively light to concentrate more on research to compensate for the heavier administrative and teaching load in my first few years and subsequent to the 10-year CRC term. Most of my administration involves supervising a research team and a well-equipped space robotics laboratory. Furthermore, I contribute to wider policy issues within my field of space engineering such as representing the university at space policy meetings and workshops at the Canadian Space Agency. I have served on the Departmental Staffing committee (twice) during the reviewing, interviewing and hiring of new members of staff (2007-2009 and 2022). This was a heavy administrative load involving ranking applications, attending interviews and consulting with other staff. One of the key attributes for Carleton is hiring the right person who will fit into the current team and contribute positively and enthusiastically - being likeable and cooperative were some of the most important qualifications. I also had until recently, additional administrative responsibilities such as being a member of the Canadian Foundation for the International Space University that, on behalf of the Canadian Space Agency, administered and awarded annual scholarships to the International Space University (ISU) summer school and MSc degree courses (Space Studies and Space Management) in Strasbourg France. I was on the Tenure & Promotions Committee in 2017/2018 to gain insights into professorial career development. I have done the rounds of various departmental committees - Aerospace Curriculum Committee, Dynamics & Controls Curriculum Committee, Graduate Scholarships Committee, Capstone Projects Committee...These are not roles I particularly relish.

An important part of our responsibility in scientific and engineering research is to communicate with the public at large who fund our activities and to whom we serve as part of society. I have been involved in media activities in the UK and Carleton University though its time-consuming nature has restricted my recent attention to it of late. I am one of the "Experts on Call" on the Carleton Newsroom that is available for journalists to call for telephone interviews – this happens on a fairly frequent basis but recently I have scaled my availability back. I have also done a number of radio and TV interviews in both Canada (CBC) and in the UK (BBC). Some highlighted examples include a CBC radio interview across four Canadian cities on Mars exploration (2010), a televised presentation to John Wilkinson then-Minister of Research & Innovation (2008), a CBC Radio interview on the All in a Day show (2009), a televised interview on BBC World's Click (2002), etc. I was recently invited to give a Pint for Science talk in Ottawa which was rather enjoyable. My more recent activities in this important area of public engagement has focussed on my current in-progress writing a popular engineering book *Manna from Heaven: How to Save Our Planet* concerning the development of in-situ resource utilisation and self-replication technology for space-based geoengineering and solar power satellites for clean energy generation. This is part of my general philosophy that engineering is central to society and that many of society's ills require engineering solutions.

I believe that engineering has suffered a diminished status since the great Victorian age (apart from a brief flourishing during the Apollo programme) when engineers were regarded as visionaries and pioneers. It is essentual to increase public recognition of engineering in society and enhance engineers' social status, and recent interest in STEM has gone some way towards this. Yet the public at large has limited contact with engineers. There is little conception of the social value of engineering in society compared with doctors, lawyers, teachers and accountants with whom people have contact in their day-to-day lives. Engineering originated in the trades and there is a perception that engineers are little more than overly-educated tradesmen. The reasons for the decline of engineers' status are many and varied, many citing cynicism towards technological progress following World War I. Despite the fact that the core of engineering training is fundamentally mathematics and science supplemented by business, management and law, scientists are held in higher esteem than engineers [US National Academy of Engineering (2005) "Educating the Engineer of 2020: Adapting Engineering Education to the New Century" *National Academies Press*, Washington DC]. One problem is that we engineers do not communicate our work to the general public as well as scientists – during the Victorian age, engineers gave public lectures. It is imperative that we communicate to the public to enhance the social standing of engineering in the community to ensure that the importance of engineering is understood and valued. Although there has been recent interest in developing strategies to encourage young people into STEM, these efforts are specifically targeted at the education system and not society as a whole. Popular science writing and inspiring television documentaries have been all the rage for a number of years – Brian Cox, Carl Sagan, Richard Dawkins, Susan Greenfield and Jim Al-Khalili are a random selection from a host of science popularisers. I am hard-pressed to think of any academic or industrial engineers who are as well known (only Bill Nigh comes to mind but he covers science rather than his original trade, engineering). Part of the problem is that there is little credit to be gained from such activities in academic or industrial engineering. Nevertheless, it is something in which the engineering community should be engaged and I believe the brunt of responsibility should lie with academic engineers. The pressure to sensationalise into "wow-wee" TV can confound and tarnish academic engineers' reputations however. I have written three recent articles for *The Conversation* as a step towards public engagement. I have established my credentials through three engineering textbooks – *An Introduction to Space Robotics* (2000), *Planetary Rovers* (2016), and *Space Technology for Astrobiology Missions* (unpublished). On that basis, I am currently working on two popular engineering book titles – *Manna from Heaven* and its sequel *The Tenth Avatar* (the latter is already contracted to Springer Publishers), both of which explore engineering and technology and their implications for the future. I believe that such popular engineering books will enhance engineering exposure in broader society.

IX. RESEARCH PROFILE

In this section, I present my publications and research activities in a narrative form. I am a space engineer whose specialist field is robotics - my research is entirely devoted to space engineering with an emphasis on robotics in its broadest context. Robotics is a strategic technology for space exploration [[1],[2],[3],[4],[5]] which covers several specific areas including autonomous exploration spacecraft [[6]], on-orbit servicing manipulation [[7]] and planetary rovers [[8]] among others. More recently, I have engaged in a new stream that integrates these other streams in an over-arching programme of in-situ resource utilisation (ISRU) and derivatives cocepts such as self-replicating machines. I work in all areas of space robotics and I try to tackle difficult core problems rather than easier peripheral problems. My specialist field – space robotics – is highly multidisciplinary which offers opportunities for research in a wide span of directions. Indeed, I believe that cross-disciplinary research projects are the richest regions for innovation and enjoy the opportunity to work at the boundaries of biomimetics and astrobiology in particular. For planetary rovers, robotics serves the deployment of scientific instruments – this requires close collaboration with scientists and an understanding of scientific goals. One continually emerging theme across much of my research is bio-inspiration, which can be appropriate in often subtle ways. I undertook a long study for ESA on the application of biomimetics to space exploration culminating in reports of over 1000 pages [[9],[10],[11]]. This included a study on a walking robot for Mars exploration [[12]] and a bio-inspired drill (addressed later). The main lesson from biology is that it does not carve up the world into mechanical and control engineering régimes - in biological animals, morphological structures have co-evolved with their control structures.

Spacecraft Autonomy

[1] Ellery A (2001) "A robotics perspective on human spaceflight" *Earth Moon & Planets* **87**, 173-190
[2] Ellery A (2002) "Multi-disciplinary field of space robotics comes of age in the UK" *IEE Professional Networks Online Library* (Robotics & Mechatronics)
[3] Ellery A (2002) "Space robotics – a broad church" *Ignition* **1** (3), 4-5
[4] Ellery A (2003) "Humans versus robots for space exploration and development" *Space Policy* **19**, 87-91
[5] Ellery A (2014) "Editorial: Special Issue on Space Robotics" *Int J Advanced Robotics Systems* (28 Feb 2014)
[6] Ellery A (2004) "Space robotics part 1: what is a robotic spacecraft?" *International J Advanced Robotic Systems* **1** (2) 118-121
[7] Ellery A (2004) "Space robotics part 2: space-based manipulators" *International J Advanced Robotic Systems* **1** (3), 213-216
[8] Ellery A (2004) "Space robotics part 3: robotic rovers for planetary exploration" *International J Advanced Robotic Systems* **1** (4), 303-307
[9] Menon C, Ayre M & Ellery A (2006) "Biomimetics - a new approach to space systems design" *ESA Bulletin* **125** (Feb), 21-26
[10] Ellery A et al (2004) "Bionics & Space Systems Design 1 – Overview of Biomimetics Technology" ESA-ESTEC Technical Note 1 (ESA Contract no 18203/04/NL/PA)
[11] Ellery A et al (2005) "Bionics & Space Systems Design 3 – Application of Biomimetics to Space Technology" ESA-ESTEC Technical Note 3 (ESA Contract no 18203/04/NL/PA)
[12] Ellery A, Scott G et al (2005) "Bionics & Space Systems Design 4 – Case Study 1 Mars Walker" ESA-ESTEC Technical Note 4 (ESA Contract no 18203/04/NL/PA)

I undertook a consultancy project for DRDC on cyber-protection of spacecraft [13,14,15] based on some of my earlier investigations into hybrid Bayesian network symbol extraction from neural networks [16]. Because neural nets are not logic-based, they should be immune to logic bombs, but neural networks are opaque to validation and verufication. Hybridising them with Bayesian networks offers the potential for incorporating/extracting symbolic logic. If it can be achieved, this technology can be applied to spacecraft autonomy in FPGA format to impart cyber-immunity against non-state aggressors yet integrate logic within its weight configuration [17]. This work is continuing with a cyber-protection private company.

Space Manipulators

I cut my teeth on space-based manipulator dynamics and control and their use in on-orbit servicing. On-orbit servicing introduces increased spacecraft availability to supplement the use of high reliability components [18] and offers a potentially commercial application of space robotics [19]. On-orbit servicing missions can be observed telescopically from the ground with characteristic observable signatures [20,21,22]. The use of manipulators mounted onto spacecraft for on-orbit servicing imposes greater complexities in the kinematics, dynamics and control of the manipulators due to the reaction forces and torques generated by the manipulator(s) on the spacecraft. During my PhD, I was concerned with the dynamic control of manipulators mounted onto spacecraft conducting grappling tasks [23]. I developed a method in which the inverse kinematic equations could incorporate dynamic parameters to accommodate the lack of a ground reference point by using a locally inertial reference frame (Fig 2) [24]. Linear compensation can be accommodated through lumped link parameters and the adoption of control moment gyroscopes for attitude stabilisation. This allowed the use of a Newton-Euler formulation of the dynamics with a computational complexity of O(n) and the computed torque control algorithm enhanced with adaptive control gains. During grasping, the reaction moments on the spacecraft platform are significant requiring the use of control moment gyroscopes rather than reaction wheels for spacecraft attitude stabilisation [25]. A subsequently published aspect of this work was

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13 Ellery A (2018) "Autonomous Mission Planning: Part 1 – Review of Current & Past AI Techniques" DRDC Space Situational Awareness Report 1

14 Ellery A (2019) "Artificial intelligence techniques – hybrid symbolic neutral network systems" DRDC Scientific Report 2, Ottawa Research Centre

15 Ellery A (2019) "Deep learning systems" DRDC Scientific Report 3, Ottawa Research Centre

16 Ellery A (2015) "Artificial intelligence through symbolic connectionism – a biomimetic rapprochement" in *Biomimetic Technologies: Principles & Applications* (ed. Ngo D), Elsevier Publishing

17 Ellery A (2019) "Hybrid artificial intelligence as a defence against cyber-interference of military satellites" *Int Astronautics Congress*, Washington DC, IAC-19,D5.4.6.x49642

18 Ellery A, Kreisel J, Summer B (2008) "The case for robotic on-orbit servicing of spacecraft: spacecraft reliability is a myth" *Acta Astronautica* **63**, 632-648

19 Ellery A, Welch C (2002) "A proposed public-private partnership for the funding of robotic in-orbit servicers" *Proc Space 2002 and Robotics 2002*, Alburquerque, New Mexico, 07291734ELLE

20 Scott R, Ellery A, Levesque M (2011) "Non-resolved detection of objects performing on-orbit servicing in geostationary orbit" *AMOS Technical Conf*, paper no BJW-RLS-CM

21 Scott R & Ellery A (2015) "An approach to ground-based space surveillance of geostationary on-orbit servicing operations" *Acta Astronautica* **112**, 56-68

22 Scott R & Ellery A (2016) "Speckle imaging for optical tracking of on-orbit servicing in geostationary orbit" *AIAA J Spacecraft & Rockets* **53** (3), 433-447

23 Ellery A (2002) "Technology of robotic in-orbit servicing" *Proc 1st Bilateral DLR-CSA Workshop on On-Orbit Servicing of Space Infrastructure Elements via Automation & Robotics Technologies* (OOS 2002), Waldrunnen, Cologne-Bonn, Germany, 1.11.30

24 Ellery A (1994) "Resolved motion control of space manipulators" *Proc 45th International Astronautics Congress*, Tel Aviv, Israel, ST-94-W2-574

25 Ellery A (2004) "Robotic in-orbit servicers - the need for control moment gyroscopes for attitude control" *Aeronautical J of Royal Aeronautical Society* **108** (1082), 207-214

awarded the George Stephenson medal and the William Sweet Smith prize by the IMechE [26]. Gravity gradient torques may also be exploited to minimise the use propellant [27].

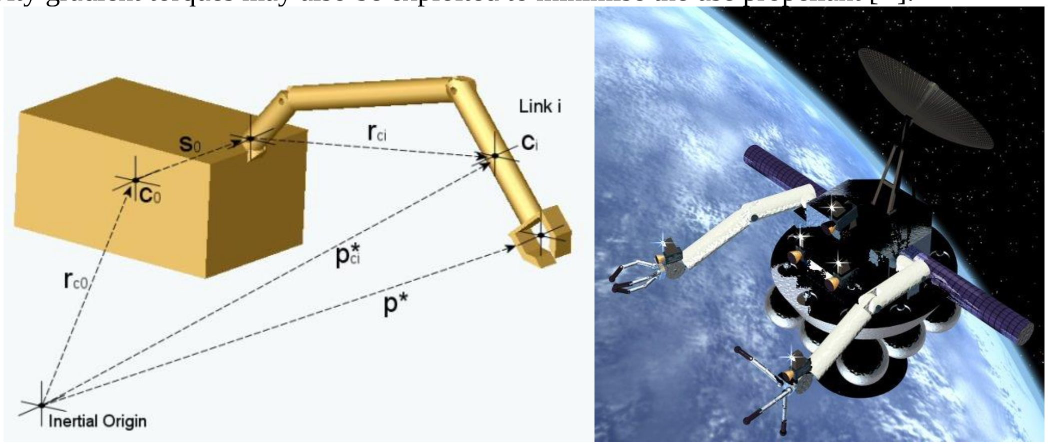

Fig 2. Freeflyer manipulator reference frames; freeflyer manipulator concept

I have also made occasional excursions into propulsion systems for robotic on-orvbit servicers [28,29]. The same technique [30] was applied to a submersible-based manipulator system with applications to Europa exploration [31]. This showed the adaptability of the approach to incorporating fluid constraints on the manipulator dynamics. Although the application of robotics to astronomy has been considered through the robotic deployment of modular detector arrays [32], we have applied the same techniques developed for controlling manipulators on spacecraft to the maintenance of inter-satellite distance to submicron accuracy using manipulator motions without the expenditure of fuel [33]. This approach will permit the adoption of interferometric constellations of spacecraft with highly stable virtual platforms to enable high resolution infrared imaging of extrasolar planets, particularly terrestrial-type planets in the habitable zone of stars (Fig 3). The same technique can be applied to the detection and measurement of gravitational wave emissions from colliding black holes.

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26 Ellery A (2004) "An engineering approach to the dynamic control of space robotic on-orbit servicers" *Proc Inst Mechanical Engineers Part G: J Aerospace Engineering* **218**, 79-98

27 Lynch B, Ellery A (2015) "Spacecraft propulsion using angular momentum transfer based on gravity gradient effects" *J Spacecraft & Rockets* **52** (2), 481-495

28 Ellery A, Welch C, Leveque N (2002) "Advanced Telerobotic Actuation System (ATLAS) in-orbit servicer propulsion options" *World Space Congress*, Houston, Texas, IAC-02-U.2.08

29 Leveque N, Welch C, Ellery A, Curley A (2003) "Trajectory simulations for thrust-vectored electric propulsion missions" *International Electric Propulsion Conf*, IEPC-3-0050

30 Lynch B, Ellery A (2008) "Kinematics and dynamics of spacecraft robotic manipulators" *Canadian Aeronautics & Space Institute (CASI) ASTRO2008*, Montreal, Canada, paper no. 89

31 Lynch B & Ellery A (2014) "Efficient control of an AUV vehicle-manipulator system: an application for the exploration of Europa" *IEEE J Oceanic Engineering* **39** (3), 552-570

32 Ellery A (2003) "Robotics in the service of astronomy" *Astronomy & Geophysics J of Royal Astronomical Society* **44** (3), 3.23-3.25

33 Ogundipe C, Ellery A (2019) "Imaging terrestrial extrasolar planets using submicron interferometric platforms" *Int Astronautics Congress*, Washington DC, IAC-19,A7.3.4.x50556

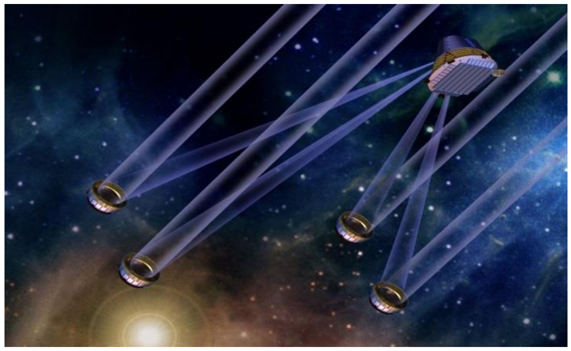

Fig 3. Darwin interferometer constellation

During my PhD, it became apparent that the implementation of closed loop force control in grasping space objects was problematic due to time delays in force feedback yielding instabilities. We developed forward predictive models to enable visual tracking of scientific targets by rover-mounted automated cameras irrespective of the movements of the rover platform. Adaptive forward models based on neural networks are necessary due to the lack of inertial measurement in the cameras for feedback (joint sensors only). This is a biomimetic approach based on an ocular reflex response. We have demonstrated the superiority of this approach on a 7 degree-of-freedom Barratt arm (Fig 4) [[34]].

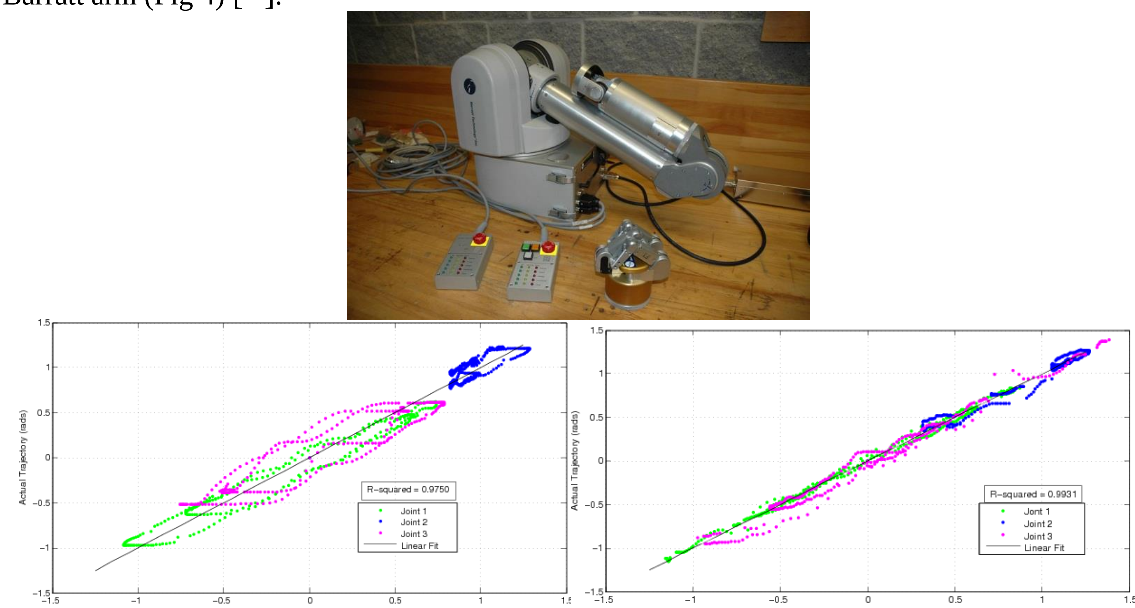

Fig 4. 7 degree-of-freedom Barratt manipulator; manipulator-mounted camera trajectory without and with feedfoward predictive model

It is known that human cerebellar forward models are capable of compensating for 500 ms time delays as predictive controllers in geostationary orbit and beyond. We have implemented neural network-based forward models for controlling space-based manipulators for the acquisition of large debris pieces [[35],[36],[37]]. This involves much more complex forward models than the forward models used for automated camera control in that they require models which incorporate applied

[34] Ross J & Ellery A (2017) "Panoramic camera tracking on planetary rovers using feedforward control" *Int J Advanced Robotic Systems* (May/Jun), 1-9

[35] Ellery A (2019) “Tutorial review on space manipulators for space debris mitigation” *Robotics* **8** (2), 34

[36] Ellery A (2020) “Tutorial review of bio-inspired approaches to robotic manipulation for space debris salvage” *Biomimetics J* 5 (2), 19

[37] Ogundipe C, Ellery A (2020) “Biomimetic control of spaceborne manipulator for debris removal and on-orbit servicing” *Proc Int Symp Artificial Intelligence, Robotics and Automation in Space*, paper no 5019

forces and torques at the end effector. We discovered that it is not feasible to transfer neural models of terrrestrial manipulators to space-based manipulators despite their similar dynamic forms so the space-based manipulator required dedicated training [38]. Eventually, we shall include the implementation of preflexes (modelling the viscoelastic properties of muscles) at the manipulator joints to provide zero-delay rapid and robust responses. Sigmoid-shaped compliance can potentially emulate "soft" robots without physical compliant material. This may exploit the direct drives on the Barratt manipulator eliminating the need for noisy end-effector force/torque sensing. This three-layer approach to manipulator control – force feedback, cerebellar-like forward models and viscoelastic compliance – promises a robust approach to manipulation to overcome the severe limits on manipulation speed for increased productivity rates. This bio-inspired manipulator control strategy should enable tactile handling, taping and folding of thermal blankets and other challenging materials during salvaging of debris spacecraft.

Planetary Rovers

The majority of my research work has been on planetary rovers from traction analysis and chassis design to autonomous rover navigation. I began investigating Bekker-Wong theory of terramechanics and its application to Mars rovers. In particular, I explored the performance of the elastic loop mobility system, a promising pre-stressed concept for tracked vehicles without bogie wheels for ESA (Fig 5) [39,40,41,42]. I then participated in ESA's ExoMars Rover Phase A study and follow-on ExoMars rover studies responsible for several aspects of the ExoMars rover [43]: (i) traction analysis [44,45] of 19 different chassis designs before selecting the RCL-D chassis [46,47]; (ii) panoramic camera for navigation functions and (iii) optic flow-based navigation.

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[38] Ogundipe C, Ellery A (2022) "Practical limits to transfer learning of neural network controllers from Earth to space environments" *Proc 42nd SGAI Int Conf on Artificial Intelligence - Lecture Notes in Artificial Intelligence* **13652**, 3-16

[39] Patel N, Ellery A, Welch C, Curley A (2002) "Preliminary analysis of mobility systems for a Mars micro-rover" *World Space Congress*, Houston, Texas, IAC-02-U.2.08

[40] Patel N, Ellery A, Welch C, Curley A, van Winnendael M (2002) "Elastic loop mobility system: an alternative for rover mobility on Mars" *Proc 7th ESA Workshop on Advanced Space Technologies for Robotics & Automation (ASTRA)*, WPP 204, ESTEC, Noordwijk, Holland, 2.2.1

[41] Ellery A (2003) "Elastic loop mobility/traction system study for Mars micro-rovers" ESA-ESTEC Final Report (ESA Contract no 16221/02/NL/MV)

[42] Patel N, Ellery A, Welch C, Curley A, van Winnendael M (2003) "Elastic loop mobility system (ELMS): concept, innovation and performance evaluation for a robotic Mars rover" *International Astronautics Congress*, Bremen, Germany, IAC-03-IAA.1.1.05

[43] Ellery A & the Rover Team (2006) "ExoMars rover and Pasteur payload Phase A study: an approach to experimental astrobiology" *International J Astrobiology* **5** (3), 221-241

[44] Ellery A (2003) "Ground-robot interaction - the basis for mobility in planetary micro-rovers" *Towards Intelligent Mobile Robots (TIMR 03) - 4th British Conference on Mobile Robotics,* University of West of England, Bristol, Paper no. 8

[45] Ellery A (2005) "Robot-environment interaction - the basis for mobility in planetary micro-rovers" *Robotics & Autonomous Systems* **51**, 29-39

[46] Ellery A, Patel N, Richter L, Bertrand R, Dalcomo Y (2005) "ExoMars rover dynamics analysis and design" *Proc 8th Int Symposium Artificial Intelligence Robotics & Automation in Space (iSAIRAS)*, Munich, Germany

[47] Ellery A, Richter L, Bertrand R (2005) "Chassis design and performance analysis for the European ExoMars rover" *Trans CSME* **29** (4), 507-518

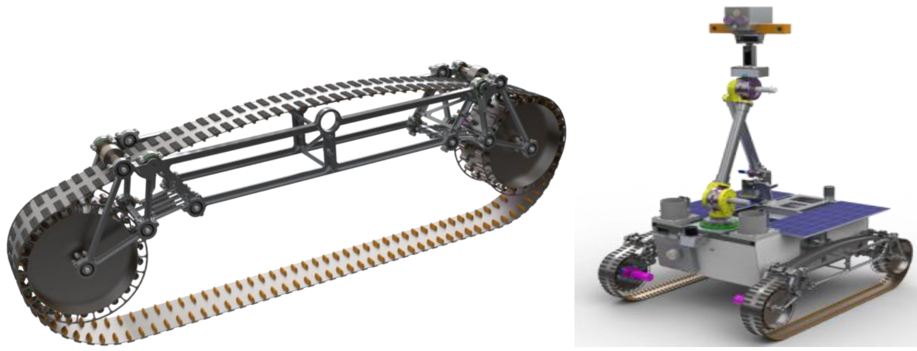

Fig 5. Elastic loop mobility system for the Kapvik micro-rover

We also developed a Rover Chassis Evaluation Tool software simulator for ESA with a European group of partners [48,49,50]. We used this tool and other analytical tools to assess a variety of Mars rover chassis designs [51,52,53] including ExoMars [54] and legged rovers [55,56,57,58]. Later, I did some work with MDA Brampton on their LEMUR (lunar exploration manned utility rover) performing traction analysis and an assessment of autonomous navigation [59,60]. Although planetary rover development is an engineering discipline, its role in the deployment of scientific instruments requires an understanding of scientific goals. I was on the science team for the ExoMars PanCam (led by MSSL) responsible for its design compatibility with a backup navigation function [61,62]. We benchmarked the computation times for several optic flow

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48 Patel N, Ellery A, Sweeting M (2004) "Rover mobility performance evaluation tool (RMPET): a systematic tool for rover chassis evaluation via the application of Bekker theory" *Proc Advanced Space Technologies for Robotics & Automation*, European Space Agency, ESTEC, Noordwijk, Holland

49 Michaud S, Richter L, Patel N, Thuer T, Huelsing T, Joudrier L, Seigwart S, Ellery A (2006) "RCET: Rover chassis evaluation tools" *Proc ASTRA*, ESA-ESTEC, Noordwijk, Holland

50 Richter L, Ellery A, Gao Y, Michaud S, Schultz N, Weiss S (2006) "A predictive wheel-soil interaction model for planetary rovers validated in testbed and against MER Mars rover performance data" *Proc 10th Int Society for Terrain-Vehicle Systems (ISTVS)*, Budapest, Hungary, pp. 343

51 Patel N, Ellery A, Sweeting M (2004) "Comparative locomotion study for Mars micro-rovers and mini-rovers" *Proc 55th IAC (International Astronautics Congress) Conference*, Vancouver, Canada

52 Patel N, Ellery A (2004) "Performance evaluation of autonomous Mars mini-rovers" *Proc Towards Autonomous Robotic Systems (TAROS 04): 5th British Conference on (Mobile) Robotics*, Rep No CSM-415, University of Essex, Colchester, Paper no. 18

53 Patel N, Scott G, Ellery A (2004) "Application of Bekker theory for planetary exploration through wheeled, tracked and legged vehicle locomotion" *Space 2004 Conf*, San Diego, California, USA, AIAA-2004-6091

54 Favaedi Y, Ellery A (2006) "3D simulation evaluation for the ExoMars rover" *Proc Towards Autonomous Robotics (TAROS 06)*, University of Surrey, Guildford, 46-55 (ed. M Witkowski, E Moxey, A Ellery), 48-55

55 Scott G, Ellery A (2004) "Biomimicry as applied to space robotics with specific reference to the Martian environment" *Proc Towards Autonomous Robotic Systems (TAROS 04) - 5th British Conference on (Mobile) Robotics*, Rep No CSM-415, University of Essex, Colchester, Paper no. 21

56 Scott G, Ellery A, Husbands P, Vincent J, Eckersley S, Cockell C, Dembo P (2004) "Bionics & Space Systems Design Project Progress Report for ESA Advanced Concepts Team" *Proc Advanced Space Technologies for Robotics & Automation*, ESTEC, Noordwijk, Holland

57 Scott G, Ellery A (2005) "Design of a biomimetic walking Mars explorer for the ESA Bionics & Space Systems Design contract (AO/1-4469/03/NL/Sfe)" *Proc Towards Autonomous Robotics (TAROS)*, Imperial College London (ed. U Nehmzow, C Melhuish, M Witkowski), 213-219

58 Scott G, Ellery A (2005) "Using Bekker theory as the primary performance metric for measuring the benefits of legged locomotion over traditional wheeled vehicles for planetary robotic explorers" *Proc Space 2005*, Long Beach, California, AIAA-2005-6736

59 Ellery A & Marshall J (2008) "Traction design options for a lunar exploration manned utility rover" MDA Technical Report LEMUR-CU02

60 Marshall J & Ellery A (2008) "Scalable autonomy options for the lunar exploration manned utility rover" MDA Technical Report LEMUR-CU01

61 Paar G, Griffiths A, Barnes D, Coates A, Jaumann R, Oberst J, Gao Y, Ellery A, Li R (2006) "Panoramic 3D vision on the ExoMars rover" *European Planetary Science Congress*, Berlin, Germany, pp. 295

algorithms which were to patch between static map imaging [63,64,65]. During this time, I investigated the concept of a Mars micro-rover as a post-Beagle 2 successor mission – Vanguard. Vanguard was based on a 30 kg microrover platform with a highly integrated scientific instrument suite designed to perform astrobiological measurements [66,67,68,69,70 ,71,72]. This involved a close collaboration with a small group of scientists (especially Dr David Wynn-Williams of the British Antarctic Survey) in developing infrared Raman spectrometers which could be integrated as part of a multi-instrument suite into the micro-rover [73,74] imposing the requirement for subsurface drilling beneath the weathered surface layer [75]. The concept of integrating Raman spectroscopy, infrared spectroscopy, confocal microscopy and laser plasma spectroscopy is still of great interest today. The Vanguard design stressed minimisation of robotic handling of samples so the instrumentation suite was based on non-contact sensors. The adoption of laser-based instruments was an important design choice as it dictated the planetary surface operations in eliminating physical sample recovery. Although the Vanguard micro-rover was subsequently superceded by the ExoMars mission, it was the precursor to the Kapvik micro-rover which I later proposed to the CSA.

Kapvik is a 30 kg flight-qualifiable end-to-end micro-rover for multiple planetary environments that was designed with COTS comonents but which requires little modification for flight (Fig 6) [76,77]. Although administered by MPB Montreal, an optics company with space instrument expertise but no prior robotics expertise, Kapvik was my concept based on Vanguard which was developed, designed and built by my research team at Carleton University. Furthermore, it was

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[62] Griffiths A, Ellery A & the Camera Team (2006) "Context for the ExoMars rover: the panoramic camera (pancam) instrument" *International J Astrobiology* **5** (3), 269-275

[63] Gao Y, Ellery A (2006) "Autonomous navigation based on optic flow for the ExoMars rover" *Proc ESA Advanced Space Technologies for Robotics & Automation (ASTRA)*, ESA-ESTEC, Noordwijk, Holland

[64] Ellery A (2007) "Optic-flow based autonomous navigation for the ExoMars rover" PPARC Final Report (CREST programme)

[65] Ellery A (2008) "Optic flow-based navigation for the ExoMars rover" *Canadian Aeronautics & Space Institute (CASI) ASTRO2008*, Montreal, Canada, paper no. 110

[66] Ellery A, Wynn-Williams D (2002) "Vanguard: a new development in experimental astrobiology" *Astronomy & Geophysics J of Royal Astronomical Society* **43** (2), 2.22-2.24

[67] Ellery A, Cockell C, Edwards H, Dickensheets D, Welch C (2002) "Vanguard - a proposed European astrobiology experiment on Mars" *Int J Astrobiology* **1** (3), 191-199

[68] Ellery A, Ball A, Cockell C, Coste P, Dickensheets D, Edwards H, Hu H, Lammer H, Lorenz R, McKee G, Richter L, Welch C, Winfield A (2002) "Vanguard - a proposal for a European post-Beagle 2 robotic Mars mission" *Proc 7th ESA Workshop on Advanced Space Technologies for Robotics & Automation (ASTRA)*, WPP 204, Cologne, Germany, 2.1.2

[69] Ellery A, Welch C, Curley A, Wynn-Williams D, Dickensheets D, Edwards H (2002) "Design options for a new European astrobiology-focussed Mars mission – Vanguard" *World Space Congress*, Houston, Texas, IAC-02-Q.3.2.04

[70] Ellery A, Ball A, Coste P, Dickensheets D, Hu H, Lorenz R, Nehmzow U, McKee G, Richter L, Winfield A (2003) "A robotic triad for Mars surface and sub-surface exploration" *Proc 7th Int Symp on Artificial Intelligence, Robotics and Automation in Space*, Nara, Japan, paper no. 2-1-3

[71] Ellery A, Ball A, Cockell C, Dickensheets D, Edwards H, Kolb C, Lammer H, Patel M, Richter L (2004) "Vanguard - a European robotic astrobiology-focussed Mars sub-surface mission proposal" *Acta Astronautica* **56** (3), 397-407

[72] Ellery A, Richter L, Parnell J, Baker A (2006) "Low cost approach to the exploration of Mars through a robotic technology demonstrator mission" *Acta Astronautica* **59** (8-11), 742-749

[73] Ellery A, Wynn-Williams D, Parnell J, Edwards H, Dickensheets D (2004) "The role of Raman spectroscopy as an astrobiological tool" *J Raman Spectroscopy* **35**, 441-457

[74] Ellery A, Wynn-Williams D (2003) "Why Raman spectroscopy on Mars? A case of the right tool for the right job" *Astrobiology* **3** (3), 565-579

[75] Ellery A, Kolb C, Lammer H, Parnell J, Edwards H, Richter L, Patel M, Romstedt J, Dickensheets D, Steel A, Cockell C (2004) "Astrobiological instrumentation on Mars - the only way is down" *Int J Astrobiology* **1** (4) 365-380

[76] Qadi A, Cross M, Ellery A, Nicol C (2012) "Smart reconfigurable all-terrain multi-mission planetary micro-rover, design and control" *Proc 16th CASI Conf ASTRO*, Quebec City, no 84

[77] Cross M, Nicol C, Qadi A, Ellery A (2013) "Application of COTS components for Martian exploration" *J British Interplanetary Society* **66** (5/6), 161-166

designed and built from scratch with a clear path to flight qualification, rather than retro-fitted from a pre-existing platform. My team's core contributions to Kapvik were the design and performance specifications, rover traction analysis, the detailed design, manufacture (in-house) and assembly of the rover chassis, main electronics box, body structure and all mechanical elements (except the robotic arm), camera/ultraviolet imager pan-tilt system, the avionics architecture design including motor controllers, avionics packaging and wiring harness routing, and adoption of FPGA computers, and much of the autonomous navigation system software including an unscented Kalman filter for multisensor fusion, vision processing and laser rangefinder processing.

Fig 6. Kapvik micro-rover: Kapvik undergoing cliff abseiling tests; Kapvik undergoing traction tests in a sandbox; Kapvik on display in front of Canada's Minister for Industry Christian Paradis; Kapvik on deployment at Canadian Space Agency's Mars Yard

Kapvik had several key features that I had proposed. The Kapvik arm, although built by our project partners, was based on my design combining the functions of a manipulator and a camera mast. The Kapvik chassis is designed to be modular and fully exchangeable to allow different chassis designs to be implemented including our detailed design for an elastic loop mobility system (not built) which is likely to be required for more rugged planetary terrains such as the high priority lunar south pole Aitken basin. The Kapvik chassis is based on an instrumented wheeled rocker-bogie design [[78],[79]] which incorporated integrated load sensors above each wheel

[78] Setterfield T, Ellery A (2010) "Potential chassis designs for Kapvik, a Canadian reconfigurable planetary microrover" *Proc ASTRO Conf*, Toronto, paper 16

[79] Setterfield T, Frasier C & Ellery A (2013) "Mechanical design and testing of an instrumented rocker-bogie mobility system for the Kapvik micro-rover" *J British Interplanetary Society* **67**, 96-104

station for slip-based automated traction control [80,81,82]. We developed a means to estimate soil cohesion and soil friction angle through wheel-soil terrain interaction during rover traverse (Fig 7) [83,84].

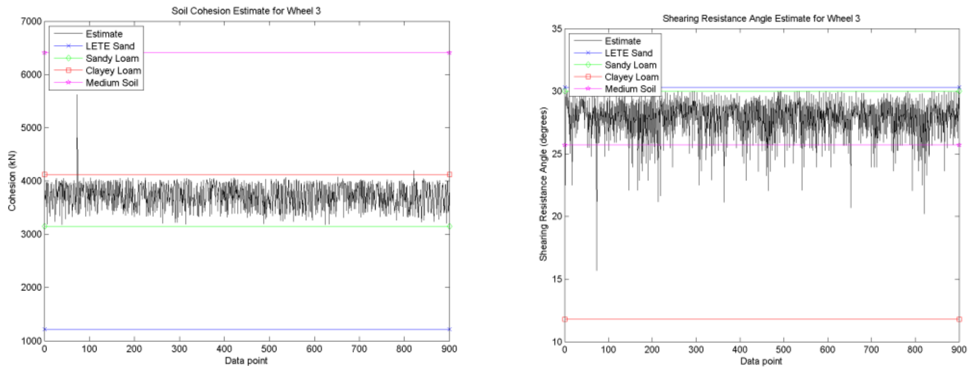

Fig 7. Extracted soil cohesion and friction angle during rover traverse at Petrie Island field trials

This capability was being developed for the online detection of water ice in the lunar regolith with the NASA RESOLVE mission. This was to be developed into a full capability – SHADE (soil hazard detection) algorithm – that integrated the above wheel-soil measurements with a predictive visual component based on wavelet/Gabor analysis within a delayed Kalman filter framework for the the lunar Resource Prospector mission (RPM) carrying the RESOLVE payload until it was cancelled in 2016 [85].

We developed autonav algorithms for lidar-based 2D self-localisation and mapping (FastSLAM 2.0) [86,87,88] for Kapvik but tested on our Husky rover platform in field trials (Fig 8). The FastSLAM technique was augmented by a extended Kalman filter-trained neural network to cope with the thorny problem of data association [89].

[80] McLean D, Ellery A (2008) "Survey of traction control systems for planetary rovers" *CSME Forum (CCToMM)*, Ottawa University, Canada

[81] Swartz M, Ellery A (2008) "Towards adaptive localisation for rover navigation using multilayer feedforward neural networks" *Canadian Aeronautics & Space Institute (CASI) ASTRO2008*, Montreal, Canada, paper no. 74

[82] Setterfield T, Ellery A (2013) "Terrain response estimation using an instrumented rocker-bogie mobility system" *IEEE Trans Robotics* **29** (1), 172-188

[83] Cross M, Ellery A, Qadi A (2013) "Estimating terrain parameters for a rigid wheel rover using neural networks" *J Terramechanics* **50** (3), 165-174

[84] Nicol C, Ellery A, Cloutis E (2014) "Online estimation of soil parameters using the Kapvik microrover" *Proc 12th Int Symp Artificial Intelligence Robotics & Automation in Space*, paper 8a-3

[85] Hipkin V, Haltigin T, Ellery A, Moores J, Samson C, Timusk M (2013) "Lunar Polar Volatiles/ISRU Mission" Canadian Space Agency RESOLVE Science Definition Document

[86] Hewitt R, Ellery A, de Ruiter A (2012) "FastSLAM on a planetary micro-rover prototype" *Proc 16th CASI Conf ASTRO*, Quebec

[87] Hewitt R, Ellery A, de Ruiter A (2012) "Efficient navigation and mapping techniques for the Kapvik analogue micro-rover" *Proc Global Space Exploration Conf*, Washington DC, GLEX-2012.P.8.p1x12478

[88] Hewitt R, Ellery A, de Ruiter A (2018) "Training a terrain traversibility classifier for a planetary rover through simulation" *Int J Advanced Robotic Systems* (Sep/Oct), 1-14

[89] Hewitt R, de Ruiter A, Ellery A (2010) "Hybridizing neural networks and Kalman filters for robotic exploration" *Proc 15th CASI Conf ASTRO*, Toronto

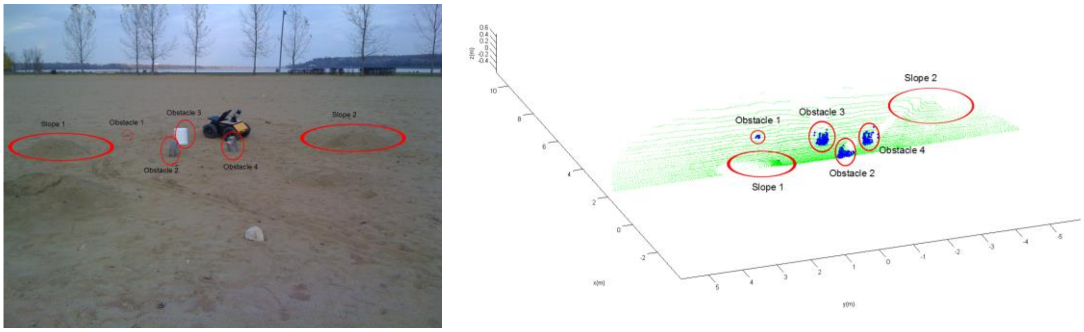

Figure 8. FastSLAM 2.0-based navigation at Petrie Island, Ottawa

From our 2D FastSLAM algorithms and the current stereovision algorithms, we have developed stereoscopic vision-based 3D SLAM algorithms for sparse outdoor environments as the basis for a rover-on-a-chip concept [90]. Path planning algorithms adopted included D* and potential field-based approaches - our tailored potential fields to enable threading of the rover through narrow gaps [91,92,93] (Fig 9) including combined manipulator-rover path planning [94].

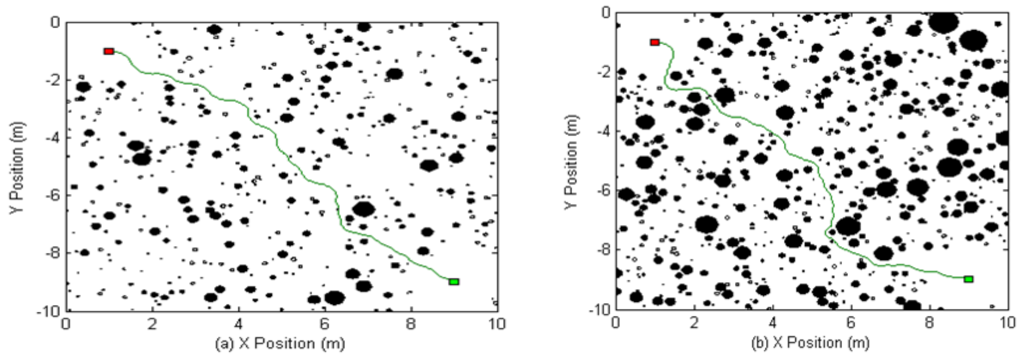

Fig 9. Potential field autonavigation through simulated Viking Lander site rock-fields

CBC televised Kapvik during its successful field trials at Petrie Island in Nov 2011 prior to its delivery to CSA. We achieved this with a budget of only $330k over 2.5 years and at all times, we were on budget and on time successfully demonstrating the viability of academic delivery of complex flight hardware and software. Six years after its delivery to the CSA, Kapvik is their only still-operational micro-rover having undertaken deeper and longer tests than its original design specification. We have also addressed several issues regarding rover operations in an underground lunar mine prospecting for buried M-type asteroidal material [95].

Planetary Drills

We are currently working with McGill University on a 3 year project to roboticise two astrobiology instruments for field testing in the high Arctic. The two instruments are newly-

[90] Molina Cabrera P & Ellery A (2015) "Towards a visual simultaneous localisation and mapping system for computationally constrained systems" (unpublished)

[91] Mack A, Ellery A (2009) "A method of real-time obstacle detection and avoidance using cameras for autonomous planetary rovers" *Towards Autonomous Robotic Systems (TAROS 09)*, Londonderry, 112-118

[92] Mack A, Ellery A (2010) "The potential steering function and its application to planetary exploration rovers" *Proc 15th CASI Conf ASTRO*, Toronto

[93] Frazier C, Baddour N, Ellery A (2014) "Assisted teleoperation and autonomous operation for planetary rovers using re-active vector equilibrium (RAVE) navigation" *Proc 65th Int Astronautics Congress*, IAC-14.A5.3-B3.6.6

[94] Lynch B, Ellery A, Nitzsche F (2008) "Two-dimensional robotic vehicle path planning based on artificial potential fields" *CSME Forum (CCToMM)*, Ottawa University, Canada

[95] Ellery A (2022) "Some key explorations in planetary rover autonomy for ISRU roles on the Moon" *Proc ASCE Earth & Space Conf*, Colorado School of Mines, Denver, 207-222

developed compact instruments – a nanopore instrument capable of detecting and characterising nucleic acids and a microbial micro-assay capable of identifying specific amino acids and proteins. Our job to three-fold : (i) build a coring drill to extract an ice sample; (ii) develop the microfluidics channels to convey the melted sample to the cryo-ichip which isolates microbial samples including flushing for multiple samples; (iii) package the instrument into an assembly suitable for deployment on a rover (Fig 10).

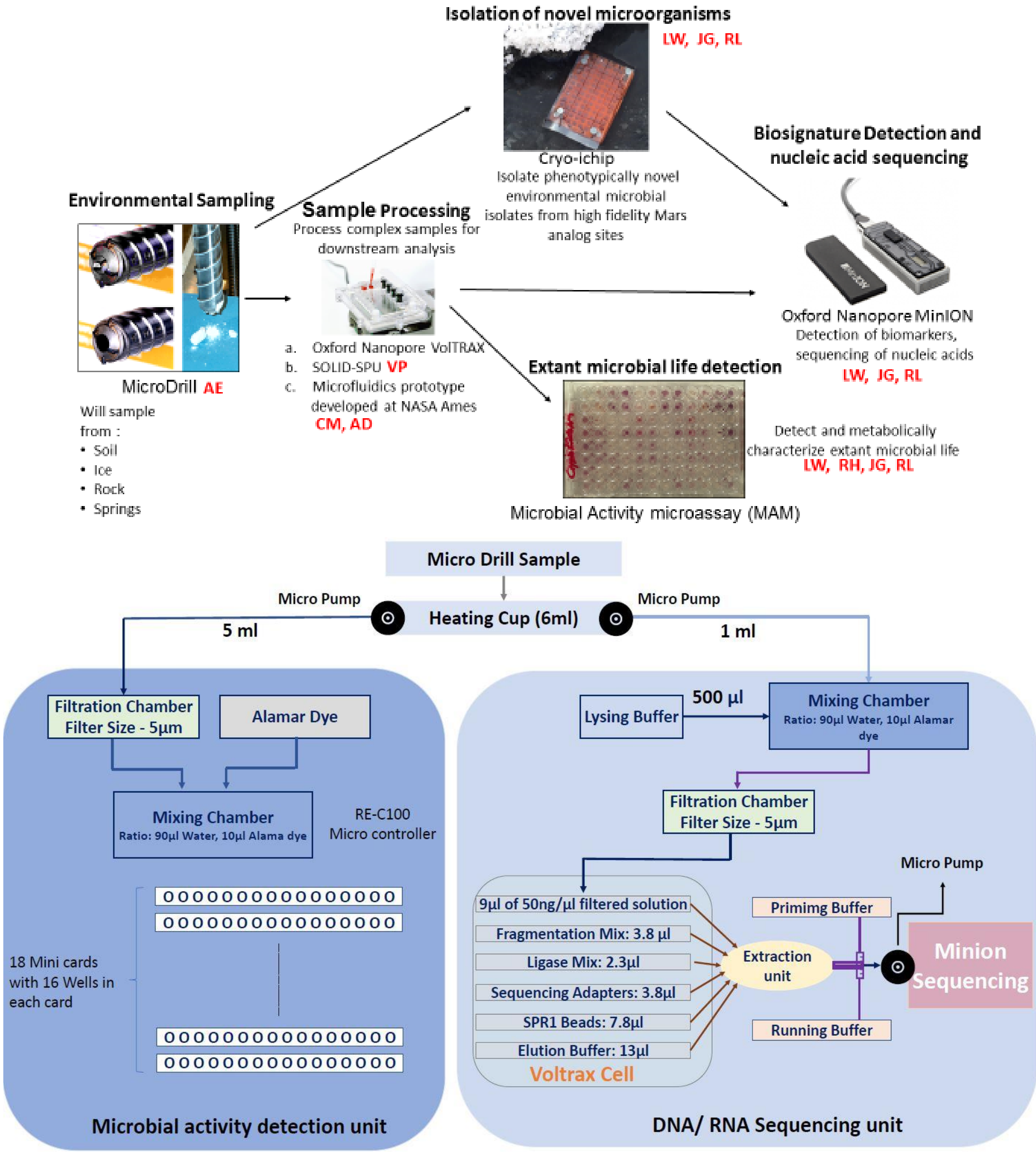

Fig 10. MicroLife detection instrument architecture

This project is in an extended phase and we have been refining the ice coring drill through testing in several Arctic field trials (Fig 11).

Fig 11. MicroLife ice coring drill

We are examining miniaturisation of the penetrator drill using a bio-inspired mechanism based on the ovipositor of the wood-wasp (Fig 12). Experimental studies had been performed by my group at Surrey Space Centre [[96],[97],[98],[99],[100][101],[102],[103]]. A detailed design was later developed for packaging the drill compactly at Carleton for Mars rover application [[104],[105],[106],[107]].

[96] Gao Y, Ellery A, Vincent J, Eckersley S (2005) "Biologically-inspired penetration/drilling/sampling system for in-situ astrobiological studies" *Proc Towards Autonomous Robotics (TAROS)*, Imperial College London (ed. U Nehmzow, C Melhuish, M Witkowski), 51-56

[97] Menon C, Lan N, Ellery A, Zangani D, Manning C, Vincent J, Bilhaut L, Gao Y, Carioso S, Eckersley S (2006) "Bio-inspired micro-drills for future planetary exploration" *Proc CANEUS*, Toulouse, France, CANEUS-2006-11022

[98] Gao Y, Ellery A, Jaddou M, Vincent J, Eckersley S (2005) "Novel penetration system for in-situ astrobiological studies" *Int J Advanced Robotic Systems* **2** (4), 281-286

[99] Ellery A, Gao Y et al (2005) "Bionics & Space Systems Design 4 – Case Study 2 Biomimetic Drill" ESA-ESTEC Technical Note 4 (ESA Contract no 18203/04/NL/PA)

[100] Gao Y, Ellery A, Jaddou M, Vincent J (2006) "Deployable wood wasp drill for planetary subsurface sampling" *IEEE Proc. Aerospace Conf*, Big Sky, MT, USA

[101] Gao Y, Ellery A, Jaddou M, Vincent J (2006) "Bio-inspired drill for planetary subsurface sampling: literature survey, conceptual design and feasibility study" *Proc Adaptation in Intelligent Systems & Biology (AISB) Conf* **2**, University of Bristol, 71-77

[102] Gao Y, Ellery A, Sweeting M, Vincent J (2007) "Bio-inspired drill for planetary sampling: literature survey, conceptual design and feasibility study" *AIAA J Spacecraft & Rockets* **44** (3), 703-709

[103] Gao Y, Ellery A, Vincent J, Eckersley S, Jaddou M (2007) "Planetary micro-penetrator concept study with biomimetic drill and sampler design" *IEEE Trans Aerospace & Electronic Systems* **43** (3), 875-885

[104] Kolb C, Lammer H, Abart R, Ellery A, Edwards H, Cockell C, Patel M (2002) "The Martian oxygen surface sink and its implications for the oxidant extinction depth" *Proc 2nd European Workshop on Exo/Astro-Biology* (ESA SP-518), Graz, Austria, 181-184

[105] Ellery A, Ball A, Cockell C, Coste P, Dickensheets D, Edwards H, Hu H, Kolb C, Lammer H, Lorenz R, McKee G, Richter L, Winfield A, Welch C (2002) "Robotic astrobiology - the need for sub-surface penetration of Mars" *Proc 2nd European Workshop on Exo/Astro-Biology* (ESA SP-518), Graz, Austria, 313-317

[106] Hopkins T, Ellery A (2008) "Drilling model and applications of space drilling" *Canadian Aeronautics & Space Institute (CASI) ASTRO2008*, Montreal, Canada, paper no. 79

[107] Hopkins T, Ellery A (2008) "Rotary and percussive drilling penetration rate prediction model verification" *CSME Forum (AM)*, Ottawa University, Canada

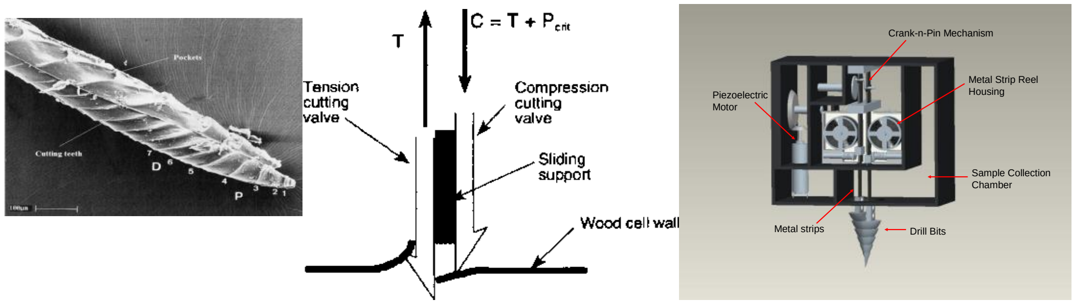

Fig 12. Wood wasp ovipositor, its mechanism and bio-inspired drill

This development work is ongoing.

Penetrators

My non-robotics space research has primarily focussed on micro-penetrators and impact-tolerant packages of scientific instruments. At Kingston University and then Surrey Space Centre, the Vanguard entry descent and landing system was analysed using a software simulation tool that we developed exploring the use of ballutes (sponsored by SSTL) [[108],[109],[110],[111]]. Indeed, the simulation software was used to attempt to localise the landing region of the crashed Beagle 2 probe. I founded the UK Micro-Penetrator Consortium involving SSC, SSTL, MSSL and Qinetiq in 2002 which now leads penetrator activity in Europe. I had also been involved in the early phases of the UK's Subglacial Antarctic Lake Ellsworth (SALE) thermal drilling experiment to deploy an ice penetrator probe 3 km below the surface ice (I was responsible for the probe's internal avionics architecture) [[112]]. I performed the initial robotic lunar exploration studies for SSTL which culminated in the UK MoonLite mission concept which incorporated four penetrators for delivery to the lunar south pole [[113],[114]]. MoonLite has been cancelled and the European JUICE mission to Europa dropped the penetrator from its payload manifest. At Carleton, I led the CSA's internal study on the concept of the micro-penetrator for planetary exploration which culiminated in a two-day workshop and a visit to the UK to meet the UK's Penetrator consortium [[115],[116],[117]]. I was appointed chair of the new Canadian Micro-Penetrator Consortium in 2011 and more recently, we have been working on two penetrator concepts. The first is a Canadian micro-penetrator with astrobiology instruments based on nanopore technology led by Magellan. We are explored the use of viffing (vector in forward flight) to define a descent

[108] Allouis E, Ellery A, Welch C (2006) "Entry descent and landing systems for small planetary missions: parametric comparison of parachutes and inflatable systems for the proposed Vanguard Mars mission" *Acta Astronautica* **59**, 911-922

[109] Allouis E, Ellery A, Welch C (2003) "Entry descent and landing systems for small planetary landers: a parametric comparison of parachutes and inflatables for the proposed Vanguard Mars mission" *Proc 5th IAA Int Conf on Low-Cost Planetary Missions* (ESA SP 542), ESTEC, Noordwijk, Holland, 289-296

[110] Allouis E, Ellery A, Welch C (2003) "Parachutes and inflatable structures: parametric comparison of EDL systems for the proposed Vanguard Mars mission" *International Astronautics Congress*, Bremen, Germany, IAC-03-Q.3B.04

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[112] Siegert M, Ellery A & the Lake Ellsworth Consortium (2006) "Exploration of Ellsworth subglacial lake: a concept for the development, organization and execution of an experiment to explore, measure and sample the environment of a West Antarctic subglacial lake" *Reviews in Environmental Science & Biotechnology* **6** (1-3), 161-179

[113] Smith A, Gowen R, Coates A, Crawford I, Scott R, Church P, Ellery A, Gao Y, Pike T (2007) "Lunar exploration with penetrators" *J Astronautical Sciences* **28** (Apr Supp)

[114] Smith A, Gowen R, Coates A, Crawford I, Scott R, Church P, Ellery A, Gao Y, Pike T (2006) "Lunar exploration with penetrators" *Proc 8th ILEWG Conf*, Beijing

[115] A. Ellery (2011) "Review and Feasibility of Micro-Penetrators for Planetary Exploration" CSA Technical Report MPC-CU1

[116] A. Ellery (2011) "Astrobiology by Micro-Penetrator: The Case for Enceladus" CSA Technical Report MPC-CU2

[117] Skulinova M, Zheng W, Ellery A, Hu Y-R, Soucy Y (2012) "Enceladus micro-penetrator mission concept" *Proc 16th CASI Conf ASTRO*, Quebec City

profile from Saturn orbit of a micro-penetrator [118] to land onto the surface of Enceladus [119] by measuring the water plume concentration to estimate the water plume structure and target the geyser source. There are three descent profiles – spiral, nested box and decaying planar oscillation – each with different Δv (fuel) cost traded against water plume modelling accuracy [120,121] (Fig 13).

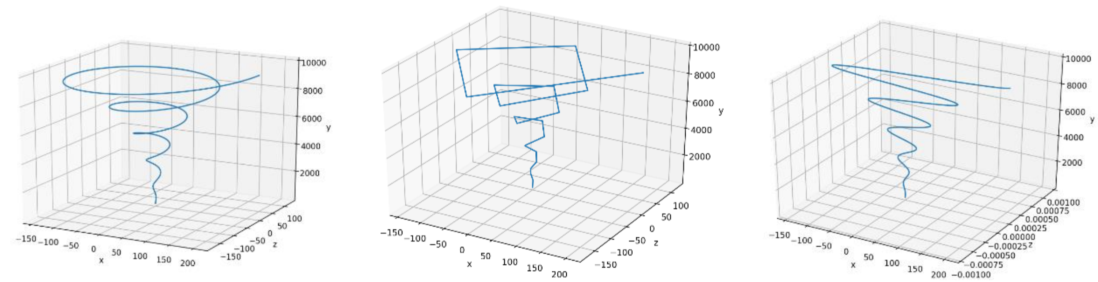

Fig 13. Viffing trajectories - spiral, nested boxes and decaying planar oscillation

SLIM (source localisation and mapping) is a variation on SLAM (self-localisation and mapping) that locates the source of odours from stochastic Gaussian models of plumes updated by measurements of vapour concentrations. SLIM can accommodate wisps in a manner that gradient descent algorithms cannot. We have explored this as the means to target a penetrator spacecraft to the tiger stripes at the south pole of Enceladus which are the sources of water plumes from a postulated near-surface ocean [122].

Robotic Science

Mars rover missions are controlled through a 3-4 day communications cycle which is wasteful and limits the scientific return of these missions – autonomous methods reduce the reliance on the ground control station. Rover operations are divided into two main phases: (i) traverse of which autonomous techniques have been described above, and (ii) science data acquisition to understand Mars and its geological history [123] – this is the province of autonomous science. The firsr choice for a Mars rover is to select promising sites for astrobiological investigation while respecting engineering constraints [124]. Kapvik has been deployed in scientific exploration trials such as magnetometric mapping and methane measurements [125,126,127]. We participated as rover specialists in Mars Methane rover analogue field trials using EX-DOC at the Jeffrey's asbestos mine (that includes serpentine which emits methane) in Quebec with a large scientific team

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118 D Grove & A Ellery (2008) "Designing a modular penetrator to accommodate multiple mission scenarios" *International Astronautics Congress* (IAC), Glasgow, UK

119 Nicol C, Ellery A, Cloutis E (2012) "Targeting Enceladus' plume – the viffing penetrator approach" *63rd International Astronautical Congress,* October 2012; Naples, Italy; paper 13061

120 Sun Y, Ellery A, Huang X (2019) "Targetting Enceladus' geyser vents using penetrators employing biomimetic plume sniffing" *Int Astronautics Congress*, Washington DC, IAC-19,A3.5.6x.49716

121 Sun Y, Ellery A, Huang X (2019) "Targeting the geysers on Enceladus by viffing descent through the icy plumes" *Advances in Space Research* **65** (7), 1863-1876

122 Sun Y, Ellery A, Huang X (2021) "Plume source localisation on Enceladus by a sequential Monte Carlo method" *AIAA J Spacecraft & Rockets* 58 (4), 1.A34982

123 Changela H, Chatzitheodoridis E, Ellery A, et al (2021) "Mars: new insights and unresolved questions" *Int J Astrobiology* 20 (6), 394-426

124 Parnell J, Cockell C, Edwards H, Ellery A (2003) "The range of life habitats in volcanic terrains on Mars" *Proc 3rd European Workshop on Exo/Astro-Biology* (SP-545), Madrid, Spain, 81-84

125 Qadi A, Samson C, Ellery A et al (2015) "Mars methane analogue mission: mission simulation and rover operations at Jeffrey mine deployment" *Advances in Space Research* **55** (10), 2414-2426

126 Hay A, Samson C, Ellery A (2018) "Robotic magnetic mapping with the Kapvik planetary micro-rover" *Int J Astrobiology* 1-10. doi:10.1017/S1473550417000209

127 Hay A, Samson C, Tuck L, Ellery A (2018) "Magnetic surveying with an unmanned ground vehicle" in press with *J Unmanned Vehicle Systems*

[128,129,130,131,132,133,134]. The goal was to demonstrate aspects of rover-mediated science data acquisition in a realistic environment. We have also investigated biomimetic tracking of methane plumes by a rover to search for the emission sources of Martian methane [135,136, 137] (Fig 14).

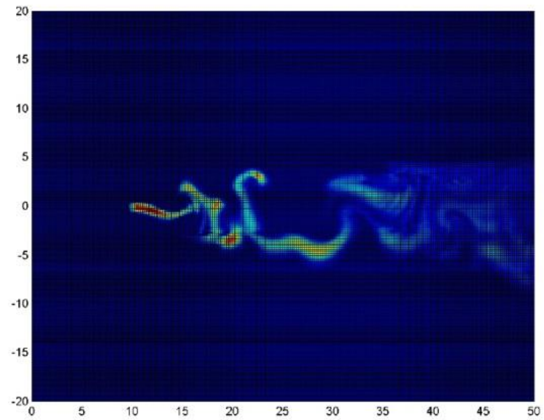

Fig 14. Mars methane plume with wisps

The science phase of rover missions may also be implemented autonomously through a robotic science/astrobiology facility [138,139]. Geological features are of primary interest to planetary scientists but colour is not used currently as dust covering on rocks on the Moon and Mars makes colour unreliable necessitating the use of visual texture analysis. We have investigated the use of Haralick parameters to perform visual texture analysis of rocks [140] then classified them using Bayesian nets [141]. This has demonstrated an 80% success rate in autonomous classification of rocks under certain restricted conditions [142]. Haralick parameters were chosen because of their reliance on entropy and information-based measures of salience that are suited to automated

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[128] Kruzelecky R, Qadi A, Ellery A et al (2012) "Mars methane mission: A field deployment in a Mars analogue environment" *16th Canadian Astronautics Conference (ASTRO 2012);* April 2012; Quebec City, QC, Canada

[129] Qadi, A, Nicol C, Mack A, Ellery A (2012) "Design and experiments for a Mars methane analogue mission rover operations" *63rd International Astronautical Congress*, October 2012; Naples, Italy; paper 15336

[130] Qadi A, Ellery A et al (2012) "Mars methane analogue mission rover operations at Jeffery mine deployment" Proc *16th CASI Conf ASTRO*, Quebec City, no 189

[131] Cloutis E, Qadi A, Ellery A et al (2012) "Mars methane analogue mission - results of first field deployment" *Proc 16th CASI Conf ASTRO*, Quebec City

[132] Cloutis E, Qadi A, Ellery A et al (2012) "Mars methane analogue mission (M3): results of the 2011 field deployment" Proc *43rd Lunar and Planetary Science Conf*, Woodlands, Texas, abstract no 1569

[133] Cloutis E, Qadi A, Ellery A et al (2013) "Mars methane analogue mission (M3): results of the 2012 field deployment" *Lunar & Planetary Science Conf 44*, abstract no 1579

[134] Cloutis E, Whyte L, Qadi A**,** Ellery A et al (2013) "How to search for methane on Mars: Results of rover field trials at Mars analogue sites" *Geological Association of Canada – Mineralogical Association of Canada Joint Annual Meeting;* May 2013; Winnipeg, MB, Canada; paper #SS17-01

[135] Nicol C, Ellery A, Cloutis E (2012) "Sniffing as a strategy for detecting life on Mars" *Proc Global Space Exploration Conf*, GLEX-2012.08.1.8x12332

[136] Ellery A, Nicol C, Cloutis E (2012) "Scent of Science: Model Creation for Odour Based Control of Robotic Vehicles" ESA Advanced Concepts Team Report 11-6301

[137] Nicol C, Ellery A, Cloutis E (2018) "Martian methane plume models for defining Mars rover methane source search strategies" *Int J Astrobiology* S1473550418000046

[138] Ellery A (2018) "Editorial for Special Issue on Robotic Astrobiology" *Int J Astrobiology* **17**, 201-202

[139] Ellery A (2018) "Robotic astrobiology – prospects for enhancing scientific productivity for Mars rover missons" *Int J Astrobiology* **17**, 1-15. doi:10.1017/S1473550417000180

[140] Sharif H, Ellery A, Samson C (2012) "Strategies for sampling of planetary materials based on images" *Proc Global Space Exploration Conf*, GLEX-2012.03.P .6x12403

[141] Sharif H, Samson C, Ellery A (2012) "Autonomous rock identification based on image processing techniques" *Proc CASI Conf ASTRO*, no 129

[142] Sharif H, Samson C & Ellery A (2015) "Autonomous rock classification using Bayesian image analysis for rover-based planetary exploration" *Computers & Geosciences* **83**, 153-167

camera slewing during rover traverses to search for opportunistic targets. This is the imaging component of active vision to complement our earlier work in feedforward camera control to foveate on regions of the visual field with high information content but eliminate local minima with a random component. This would essentially incorporate science acquisition during the rover traverse [143,144,145] – currently, rover traverses are not conducted with a science acquisition mode. We have also been examining the use of Gabor filter banks [146] and wavelets [147] which have demonstrated the ability to track sedimentary bedding formations and extracting folds, faults and texture analysis of rocks with Bayesian classifiers. Curiously the more sophisticated Gabor filtering yields only a 70% successful classification rate compared with Haralick parameters. The Bayesian network must be enhanced to accommodate online learning. To that end, we are attempting to merge Bayesian networks with neural networks to enhance the performance of the Bayesuian network through learning [148]. If further developments are successful, it will introduce greater autonomous decision-making capabilities to rovers augmented by expert-like systems that can learn to select scientific targets [149]. We have developed two scientific instruments: (i) a prototype Raman spectrometer for laboratory mineral analysis; (ii) a prototype tuned diode laser absorption spectrometer (TDLAS) for detecting in-situ water on the Moon [150].

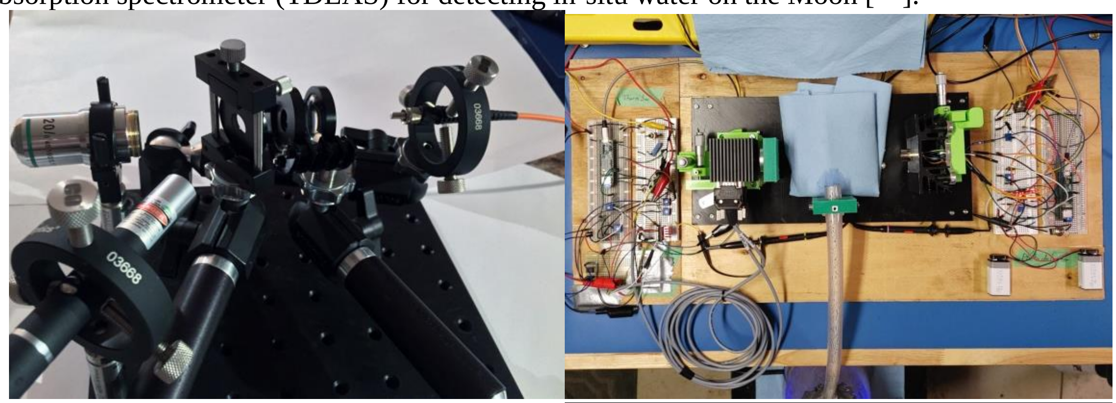

Fig 15. In-house Raman spectrometer; (b) in-house benchtop TDLAS

We have built a microfluidics distribution systems for MicroLife, μ-MAMA (Fig 13). The proposed micro-life subsystem includes a micropump as the drive mechanism of the fluid from a heating cup to a filtration chamber. The pump flow rate required for this application is in the microliter (μl) range with a maximum flow rate of approximately 40-60 μl. We are using the RP-TX series micropump manufactured by Takasago Electric Inc. We used AlamarBlue reagent as a

[143] Gallant M, Ellery A, Marshall J (2011) "Science-influenced mobile robot guidance using Bayesian networks" *Proc 24th Canadian Conf on Electrical & Computer Engineering*, Canada

[144] Gallant M, Ellery A, Marshall J (2013) "Rover-based autonomous science by probabilistic identification and evaluation" *J Intelligent & Robotic Systems* **72** (3), 591-613

[145] Gallant M, Ellery A, Marshall J (2010) "Exploring salience as an approach to rover-based planetary exploration" *Proc ASTRO Conf*, Toronto, Canada

[146] Tettenborn A & Ellery A (2017) "Onboard autonomous geological identification of rocks for planetary rovers" *Proc Advanced Space Technology for Robotics & Automation (ASTRA)*, Leiden, Holland

[147] Tettenborn A & Ellery A (2018) "Comparison of Gabor filters and wavelet transform methods for extraction of lithological features" *Proc Int Symp Artificial Intelligence Robotics & Automation in Space*, Madrid, Spain, paper no. P9

[148] Tettenborn A, Ellery A (2021) "AI methods of autonomous geological target selection in the hunt for signs of extraterrestrial life" *Lecture Notes in AI* **13101**, 103-116, Cambridge, UK (V)

[149] Ellery A (2010) "Selective snapshot of state-of-the-art artificial intelligence and robotics with reference to the Icarus starship" *J British Interplanetary Society* **62**, 427-439

[150] Gmerek A, Ellery A, Cloutis E, Thibodeau B (2022) "Proof-of-concept tabletop TDLAS instrument for the detection of H_2O in lunar regolith for the Canadian MAPLE project" *Proc 73rd Int Astronautics Congress*, Paris, IAC-22.A3.IPB.46.x67980

resazurin-based solution that acts as an indicator of the reducing power of living cells to quantify viability. The AlamarBlue reagent and the sample are thoroughly mixed in a ratio of 10:90 μl using an in-house lysing device based on a slider-crank oscillates at 4000 rpm for about 60-90 seconds. We have examined the utility of μ-MAMA in the context of astrobiollogical investigation of Enceladus [151].

Fig 16. μ-MAMA instrument

We are also examining the prospect of miniaturising and robustifying this instrument package for accommodation into an Enceladus penetrator.

In-Situ Resource Utilisation, Additive Manufacturing & Self-Replication

My newest research stream has grown dramatically – in-situ resource utilisation (ISRU) and its ultimate expression, the development of a self-replicating machine. Although asteroids are attractive targets for the mining of resources [152,153], the Moon offers certain advantages [154]. In particular, a wide range of metal alloys can be leveraged from lunar minerals [155]. My ISRU activities began with the MPB Ltd's LORE (lunar origins and resource exploitation) multi-spectrometer (UV/VIS/IR) instrument for which my group was responsible for the design of the shape memory alloy micro-actuators mechanism to control a micro-mirror to steer the optical signals from a drill-mounted fibre-optic cable. LORE was designed to detect the lunar mineral ilmenite which represents a potential source of oxygen and iron/titanium alloy (for flight on JAXA's Selene-2 but it was not selected) [156,157]. We also designed, constructed and operated an experimental setup for MPB Ltd to test dust seals on the LORE instrument to ensure that no dust contamination would occur to any internal mechanisms [158,159]. We were selected as part of the science definition team for the Canadian contribution to the American RESOLVE (regolith and environment science with oxygen and lunar volatiles extraction) payload of its Resource

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151 Sondhiya S, Ellery A (2019) "Direct astrobiological sampling of Enceladus' subsurface vents for the MicroLife instrument suite" *Int Astronautics Congress*, Washington DC, IAC-19,A1.6.9.x50396

152 Ellery A (2012) "Invited Commentary: Asteroid Ho!" *J British Interplanetary Society* **65** (2/3), 1-2

153 Ellery A, Lowing P, Mellor I, Conti M, Wanjara P, Bernier F, Kirby M, Carpenter K, Dillon P, Dawes W, Sibille L, Mueller R (2018) "Towards in-situ manufacture of magnetic devices from rare earth materials mined from asteroids" *Proc Int Symp Artificial Intelligence Robotics & Automation in Space*, Madrid, Spain, paper no. 10c-1

154 Ellery A, Crawford I, Burchell M, Cloutis E (2018) "Quo Vadis? The Moon may offer superior in-situ resource utilisation prospects than asteroids" submitted to *16th Reinventing Space Conf*, London, UK

155 Ellery A (2018) "Lunar in-situ resource utilisation – the key to human salvation on Earth" *ASCE Earth & Space Conf*, Cleveland, Ohio (10-13 Apr 2018)

156 Kruzelecky R, Wong B, Zou J, Haddad E, Jamroz W, Cloutis E, Strong K, Ellery A, Ghafoor N, Ravindran G (2010) "LORE: Lunar Origins & Resource Explorer" *AAS 10-4677*

157 Kruzelecky R, Ellery A et al (2012) "LORE: lunar origins resource explorer science payload" *Proc GLEX Conf*, Washington DC, GLEX-2012.02.1.8x12372

158 Kruzeklecky R, Wong B, Aissa B, Haddad E, Jamroz W, Cloutis E, Rosca I, Hoa S, Therriault D, Ellery A (2010) "MoonDust lunar dust simulation and mitigation" *AIAA-2010-764033*

159 Kruzelecky R, Cloutis E, Hoa S, Therriault D, Ellery A, Xian Jiang X et al (2011) "Project MoonDust: characterisation and mitigation of lunar dust" *Proc 41st Int Conf Environmental Systems*, AIAA 2011-5184

Prospector mission (RPM). Our role our measurements of soil cohesion and friction angle to detect water ice in lunar regolith to locate drilling sites. Howeveer, RPM was cancelled.

Expansion into space is hindered by prohibitive launch costs. The current commercial ticket price to the Moon's surface is $750k/kg which is prohibitive. The only solution is to industrialise the Moon using local in-situ resources (Fig 17).

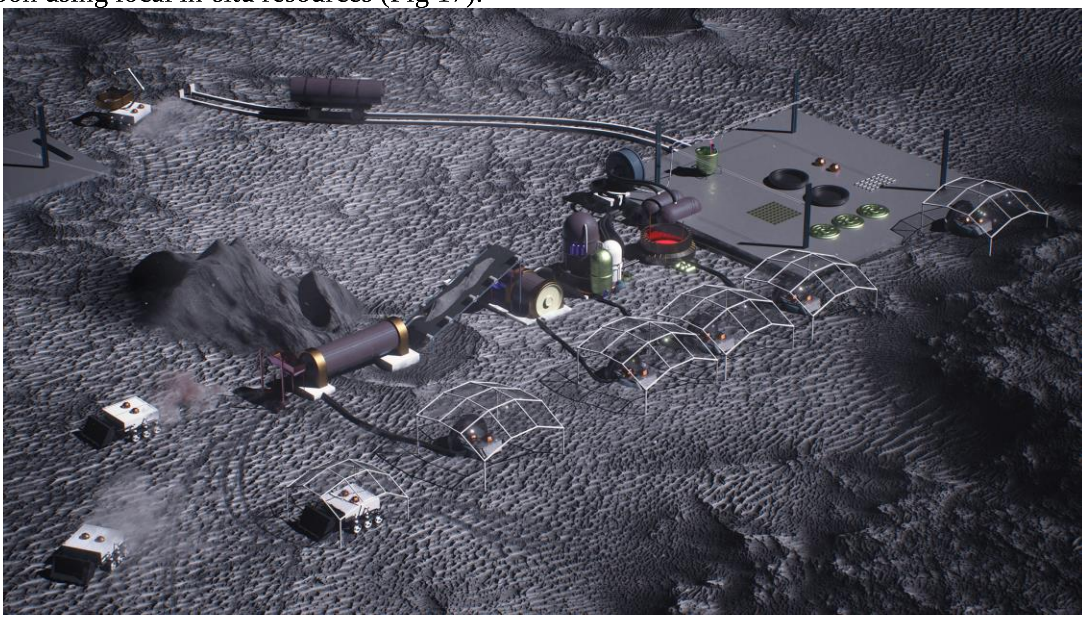

Fig 17. Lunar industrialisation

This cannot be achieved without severing the Earth supply chain. Without industrial infrastructure transported to the Moon at enormous capital cost, the industrialisation process must be grown in-situ. The self-replicating machine [160] exhibits two highly desirable characteristics: (i) its self-replication property gives it exponential growth in productive capacity toward zero specific cost [161,162,163]; (ii) its universal construction property gives it effectively infinite productive reconfigurability [164]. The most critical constraints for self-replication are matter, energy and information closure which impose strict sustainability criteria [165]. The first step to réalisation of a self-replicating machine is to devise a lunar demandite list of material functionality [166]. Demandite must be sufficient to construct a generic spacecraft using only resources on the Moon including buried asteroidal material (Fig 18).

160 Ellery A (2016) "Are self-replicating machines feasible?" *AIAA J Spacecraft & Rockets* 53 (2), 317-327
161 Ellery A (2018) "Extraterrestrial 3D printing and in-situ resource utilisation to sidestep launch costs" *J British Interplanetary Society* **70** (9), 337-343
162 Ellery A (2017) "Space exploration through self-replication technology compensates for discounting in NPV cost-benefit analysis – a business case?" *New Space J* **5** (3), 141-154
163 Ellery A (2020) "The prepper's way of space exploration with zero specific cost" *Proc AIAA ASCEND Conf*, AIAA 2020-4168
(https://arc.aiaa.org/eprint/YUWMJHF57GSIPYJBST4S/full/10.2514/6.2020-4168)
164 Ellery A (2021) "Universal construction on the Moon" *RISpace*, London, UK (V)
165 Ellery A (2020) "Sustainable lunar exploration through self-replicating robots" *Proc Int Symp Artificial Intelligence, Robotics and Automation in Space*, paper no 5006
166 Ellery A (2022) "Lunar demandite – you gotta make this using nothing but that" *Proc ASCE Earth & Space Conf*, Colorado School of Mines, Denver, 743-758

Functionality (mass fraction)	Lunar-Derived Material
Tensile structures (25%)	Wrought iron Aluminium
Compressive structures (+50%)	Cast iron Regolith + binder
Elastic structures (trace)	Steel springs/flexures Silicone elastomers
Hard structures (3%)	Alumina
Thermal conductor straps (1%)	Fernico (e.g. kovar) Nickel Aluminum
Thermal radiators (3%)	Aluminium
Thermal insulation (3%)	Glass (SiO_2 fibre) Ceramics such as SiO_2
High thermal tolerance (4%)	Tungsten Alumina
Electrical conduction wire (7%)	Aluminium Fernico (e.g. kovar) Nickel
Electrical insulation (1%)	Glass fibre Ceramics (SiO_2, $Al_2O_3$and TiO_2) Silicone plastics Silicon steel for motors
Active electronics devices (vacuum tubes) (12%)	Kovar Nickel Tungsten Fused silica glass
Magnetic materials for actuators (5%)	Ferrite Silicon steel Permalloy
Sensory transducers (5%)	Resistance wire Quartz Selenium
Optical structures (11%)	Polished nickel/aluminium Fused silica glass lenses
Lubricants (trace)	Silicone oils Water
Power system (20%)	Fresnel lens + thermionic conversion Flywheels
Combustible fuels (+250%)	Oxygen Hydrogen

Fig 18. Demandite list of functional materials for spacecraft subsystems with propoertional allocations

The second step is to construct an efficient lunar industrial ecology employing closed feedback loops that processes raw lunar material into pure compounds while minimising waste [[167]] (Fig 19).

[167] Ellery A (2020) "Sustainable in-situ resource utilisation on the Moon" *Planetary & Space Science* **184** (4), 104870

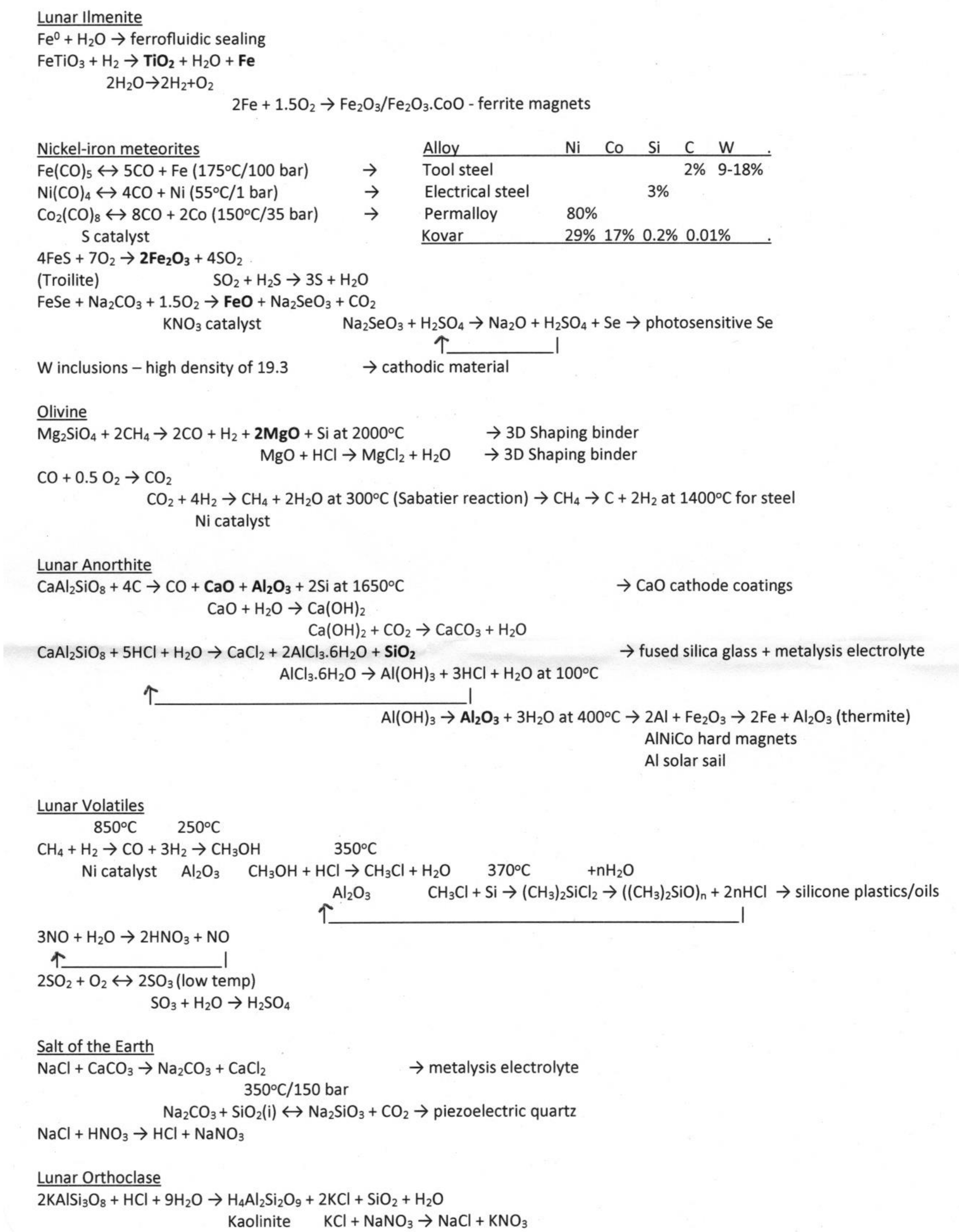

Fig 19. Lunar industrial ecology

The universal construction property requires complex reconfigurability in this industrial ecology [[168],[169]]. All oxides are subjected to a single process, the FFC electrochemical process, to reduce

[168] Ellery A (2021) "Bio-inspired "metabolism" for a lunar industrial ecology based on genetic regulatory networks" *RISpace*, London, UK (V)

[169] Ellery A (2021) "Are there biomimetic lessons from genetic regulatory networks for developing a lunar industrial ecology?" *Biomimetics J* **6** (3), 50

oxides to multiple high purity metal powders (Fig 20) [170,171,172]. This is the key to sustainable in-situ resource utilisation [173].

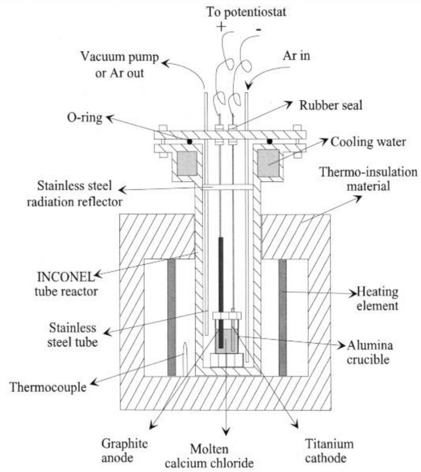

Fig 20. Metalysis FFC process

The extracted purified sintered raw material consitutes feedstock to suites of 3D printers to manufacture parts, components and systems. 3D printing may constitute a universal constructor mechanism (which equates to a self-replicating machine) [174,175,176]. Based on von Neumann's robotic self-replicator model, we require two fundamental components to realise all mechatronic systems – vacuum tubes for both computational electronics and some sensors and electric motors for general actuation. Inspired by the RepRap 3D printer which can print its own plastic parts, we adopted 3D printing as the central manufacturing technology for universal construction. To demonstrate universal construction [177], it suffices to demonstrate construction of sensors, actuators and electronics to realise robotic systems using the lunar material repertoire

[170] Ellery A, Lowing P, Wanjara P, Kirby M, Mellor I, Doughty G (2017) "FFC Cambridge process with metal 3D printing as universal in-situ resource utilisation" *Proc Advanced Space Technology for Robotics & Automation (ASTRA)*, Leiden, Holland

[171] Ellery A, Lowing P, Wanjara P, Kirby M, Mellor I, Doughty G (2017) "FFC Cambridge process and metallic 3D printing for deep in-situ resource utilisation – a match made on the Moon" *Proc Int Astronautics Congress*, Adelaide, Australia, IAC-17-D4.5.4x39364

[172] Ellery A, Mellor I, Wanjara P, Conti M (2022) "Metalysis FFC process as a strategic lunar in-situ resource utilisation technology" *New Space J* **10** (2), 224-238

[173] Ellery A (2018) "Sustainability through leveraging of extraterrestrial resources" *IEEE Conf Technologies for Sustainability* 8671386

[174] Ellery A (2015) "Prospects for a self-replication infrastructure on the Moon using in-situ resources and 3D printing technology" *Proc Space Resources Roundtable XVI/Planetary & Terrestrial Mining Sciences Symp*, Montreal, paper 11

[175] Ellery A (2015) "Notes on extraterrestrial applications of 3D-printing with regard to self-replicating machines" *Proc IEEE Int Conf Automation Science & Engineering (CASE)*, Gothenburg, 930-935

[176] Ellery A (2016) "Progress towards 3D printed mechatronic systems" *Proc IEEE Int Conf Industrial Technology with Symp on 3D Printing*, Tapei, Taiwan, pp. 1129-1133

[177] Ellery A (2017) "Universal construction based on 3D printing electric motors: steps towards self-replicating robots to transform space exploration" *IEEE Int Symp Robotics & Intelligent Sensors (IRIS)*, Ottawa, Canada, 81-85

[178,179,180,181] (Fig 21). This would effectively complete self-replication of the RepRap beyond its plastic parts [182,183].

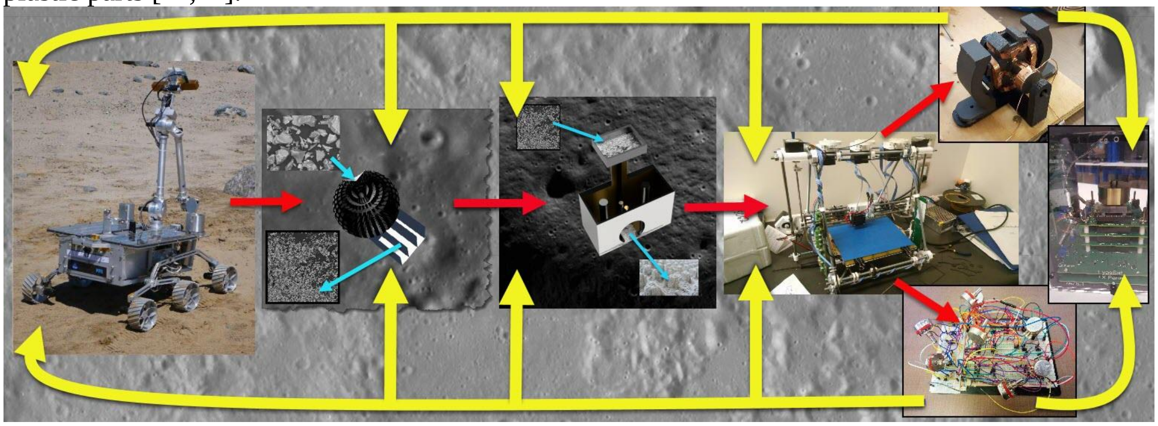

Fig 21. Sensors, electronics and motors are fundamental components of all kinematic machines

After initially considering and rejecting soft actuators [184,185], we underwent a number of different electric motor prototypes [186,], and then successfully 3D printed a complete electric motor using multiple 3D printing methods [187] (Fig 22).

178 Ellery A (2016) "John von Neumann's self-replicating machine – critical components required" *Proc IEEE Int Conf Systems Man & Cybernetics*, Budapest, Hungary, 314-319

179 Ellery A (2017) "Self-replicating machines: from theory to practice" *Proc Planetary & Terrestrial Mining Science Symp/Space Resources Roundtable*, paper no 1661

180 Ellery A (2017) "Building physical self-replicating machines" *Proc European Cong Artificial Life*, Lyon, France

181 Ellery A (2018) "The machine to end all machines – towards self-replicating machines on the Moon" *Proc IEEE Aerospace Conf*, Big Sky, MT, paper no. 2032-2.0602

182 Ellery A (2014) "Manna from heaven – preliminary efforts for a self-replicating 3D printer for lunar in-situ resource utilisation" *Proc 12th Int Symp Artificial Intelligence Robotics & Automation in Space,* paper 7a-3

183 Ellery A (2016) "How to build a self-replicating machine on the Moon" *Proc ASCE Earth & Space Conf*, Orlando, USA

184 Lynch B, Jiang X-X, Ellery A, Nitzsche F (2016) "Characterisation, modelling and control of NiTi shape memory alloy based on electrical resistance feedback" *J Intelligent Material Systems & Structures* DOI: 10.1177/1045389X16633764

185 Ellery A (2015) "Ultimate smart system – steps towards a self-replicating machine" *Proc 5th Int Conf Smart Materials & Structures,* 225-234

186 Elaskri A & Ellery A (2018) "Developing techniques to 3D print electric motors" *Proc Int Symp Artificial Intelligence Robotics & Automation in Space*, Madrid, Spain, paper no. 10c-2

187 Elaskri A, Ellery A (2020) "3D printed electric motors as a step towards self-replicating machines" *Proc Int Symp Artificial Intelligence, Robotics and Automation in Space*, paper no 5020

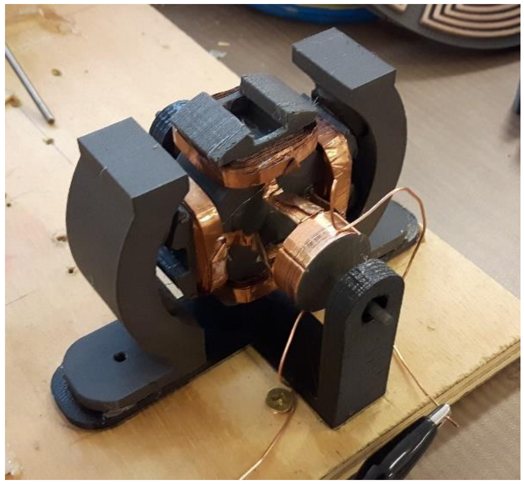

Fig 22. 3D printed electric motor

Electric motors provide the basis for building an assortment of kinematic machines including 3D printers and self-assembling systems. We have used of our earlier 3D printed motor versions (with standard wire coils) to demonstrate simple self-assembly based on a 3D printed TRIGON-type panel [188] (Fig 23).

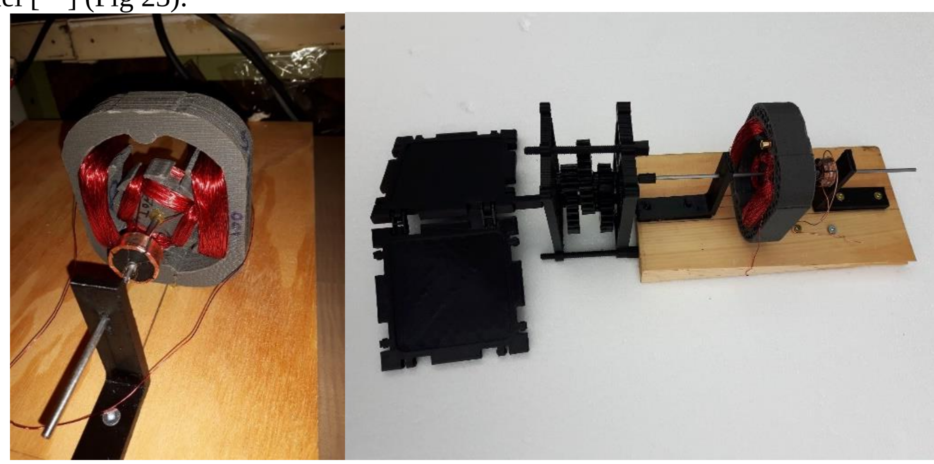

Fig 23. 3D printed soft magnet rotor and stator motor with wire coils connected via 3D printed gearing to a 3D printed deployable TRIGON panel

The next issue is the problem of 3D printing electronic controllers. After discarding printable polymer-based electronics as a computational medium, vacuum tubes were selected due to the challenges in manufacturing transistors on the Moon [189]. To reduce the hardware footprint of Turing-complete hardware based on vacuum tubes, analogue neural networks were adopted as the basic computational architecture which we have implemented as neural circuitry for controlling a desktop rover from off-the-shelf components (op-amps) [190] (Fig 24).

[188] Ellery A, Elaskri A (2019) "Steps towards self-assembly of lunar structures from modules of 3D printed in-situ resources" *Int Astronautics Congress*, Washington DC, IAC-19,D4.1.4.x49787

[189] Ellery A (2022) "Is electronics fabrication feasible on the Moon?" *Proc ASCE Earth & Space Conf*, Colorado School of Mines, Denver, 759-772

[190] Larson S, Ellery A (2015) "Trainable analogue neural network with application to lunar in-situ resource utilisation" *Proc Int Astronautics Federation Congress*, Jerusalem, IAC-15-D3.3.6

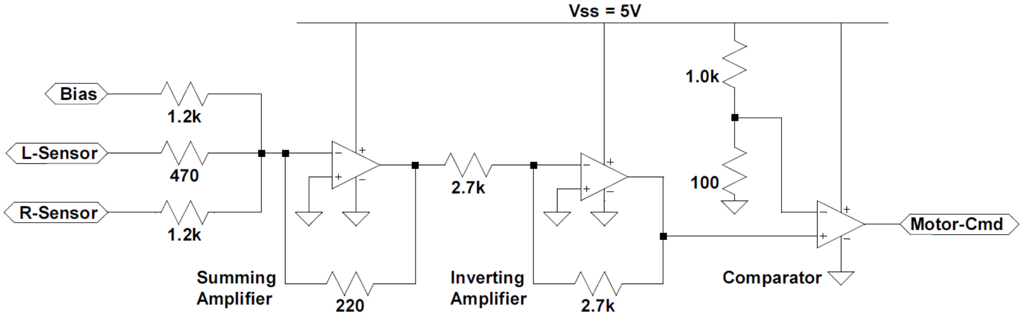

Figure 24. Single neuron analogue neural circuit

We have determined that this architecture can be scaled to address autonomous navigation through an arbitrary rockfield [191]. We have also successfully implemented the backpropagation learning algorithm in circuitry [192,193] (Fig 25).

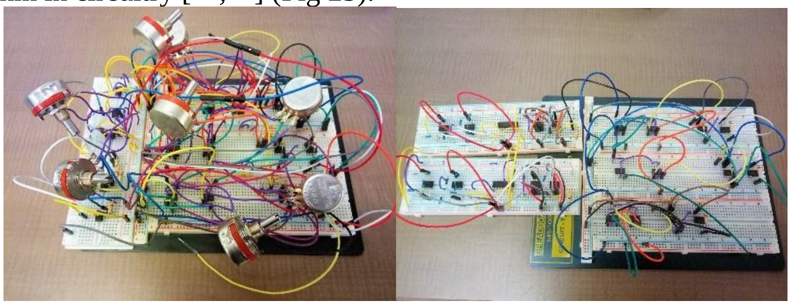

Fig 25. Forward and backward backpropagation circuits

We have yet to 3D print a vacuum tube but have been characterising a macroscopic vacuum tube, the magnetron for eventual printing. Vacuum tubes also provide the basis for arrays of photomultiplier tubes augmented with motorised active vision to enhance their resolution [194] thus completing the sensors-electronics-motor triumvirate of robotics.

We have been developing our in-house high rigidity 3D printer to simultaneously print metal and silicone plastic – 3D printer is complete with motors, gantry and work bed but the printing and milling heads are still under development (Fig 26). We have demonstrated the use of Fresnel lenses to melt aluminium-zinc (to prevent oxidation) using only solar energy and the laying of alumnium tracks onto silicone plastic substrates demonstrating the principle of simultaneous 3D printing of aluminium and silicone plastics for both electrical and mechanical applications.

[191] Ellery A (2022) "Neural computational architecture from in-situ resources for planetary exploration" *Proc 73rd Int Astronautics Congress*, Paris, IAC–22.D4.5.x68581

[192] Prasad V, Ellery A (2020) "Analogue neural network architecture for in-situ resourced computing hardware on the Moon" *Proc Int Symp Artificial Intelligence, Robotics and Automation in Space* (iSAIRAS), paper no 5005

[193] Ellery A (2022) "Bootstrapping neural electronics from lunar resources for in-situ artificial intelligence applications" *Proc 42nd SGAI Int Conf on Artificial Intelligence - Lecture Notes in Artificial Intelligence* **13652**, 83-97

[194] Ellery A (2022) "The "sensible" way to construct robots from lunar resources" *Proc 73rd Int Astronautics Congress*, Paris, IAC-22.D3.2B.x68580

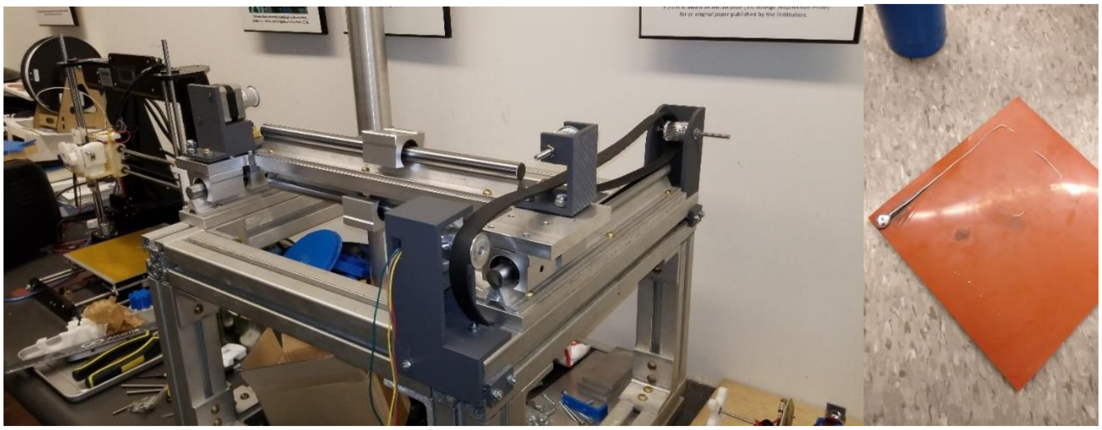

Figure 26. (a) High rigidity 3D printer; (b) Fresnel-lens melted aluminium tracks on silicone substrates

Any lunar infrastructure will require energy resources – solar concentrator-thermionic conversion for solar energy generation and flywheels for energy storage utilise the same components required for mechatronics including sensors and motors respectively (an example of exaptation) [195,196]. One way to exploit universal construction is to build a lunar base using 3D printing methods [197,198]. As well as habitat construction, some lunar resources can supplement closed ecological life support systems [199,200]. 3D printing offers sophisticated in-situ medical and life support [201]. The raison d'etre for industrialising the Moon is to circumvent the launch costs of building solar power satellites to provide clean energy to Earth [202,203,204,205,206] and, if necessary, implement space-based geoengineering technologies [207,208,209]. This combined approach could

195 Ellery A (2019) "In-situ resourced solar power generation and storage for a sustainable Moon Village" *Int Astronautics Congress*, Washington DC, IAC-19,C3.4.4.x49639

196 Ellery A (2021) "Generating and storing power on the Moon using in-situ resources" *Proc IMechE J Aerospace Engineering* 236 (6), 1045-1063

197 Ellery A (2019) "The way of indigenous peoples – 3D printing sustainable lunar bases from in-situ resources" *Int Astronautics Congress*, Washington DC, IAC-19,A1,7,2,x49637

198 Ellery A (2021) "Leveraging in-situ resources for lunar base construction" *Canadian J Civil Engineering* 49 (5), 657-674

199 Ellery A (2021) "Complementarity of a CELSS and a closed loop industrial ecology system (CLIES) on the Moon" *RISpace*, London, UK (V)

200 Ellery A (2021) "Supplementing closed ecological life support systems with in-situ resources on the Moon" *Life* **11** (8), paper 770

201 Ellery A (2021) "Applications of 3D printing to frontier space medicine and omnivory nutrition for lunar and martin habitats" *J British Interplanetary Society* **74**, 342-351

202 Ellery A (2016) "Solar power satellites for clean energy enabled through disruptive technologies" *Proc 23rd World Energy Congress (Award Winning Papers)*, Istanbul, Turkey, 133-147

203 Ellery A (2017) "Exponential populations of solar power satellites tending to zero specific cost" *Proc Int Astronautics Congress*, Adelaide, Australia, IAC-17-C3.1.8x38036

204 Ellery A (2018) "Solar power satellites: reconsideration as renewable energy source based on novel approaches" in press with *Proc 18th World Renewable Energy Congress*, Kingston-upon-Thames, UK

205 Ellery A (2022) "Solar power satellites - rotary joints, magnetrons and all - from lunar resources?" *Proc ASCE Earth & Space Conf*, Colorado School of Mines, Denver, 773-788

206 Ellery A (2022) "Solar power satellites – implications of rotary joints" *Proc 73rd Int Astronautics Congress*, Paris, IAC-22.C3.1.x67494

207 Ellery A (2016) "Low-cost space-based geoengineering: an assessment based on self-replicating manufacturing of in-situ resources on the Moon" *Int J Environmental, Chemical, Ecological, Geological and Geophysical Engineering* 10 (2), 278–285

208 Ellery A (2017) "Low-cost space-based geoengineering – a necessary albeit unwelcome solution to climate change" *Proc IAF Global Space Exploration Conf {GLEX)*, Beijing, China

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potentially solve climate change problems in the near and long-term [210]. Human exploration of Mars is the end goal for space exploration [211,212,213,214]. Self-replicating machines can be sent to Mars to construct a Martian infrastructure [215]. It also offers an effective solution to asteroid impact mitigation [216,217]. Finally, it offers the potential for implementing peta-projects on Earth at low cost [218]. The self-replicating machine introduces some unique biomimetic issues [219,220,221,222,223] by implementing a uniquely-biological characteristic. In effect, it may be considered a lifeform that adopts engineering materials rather than organic materials [224,225]. The threat of uncontrolled replication must be addressed. There are three main approaches: kill-switches and error detection and correction coding [226] and the implementation of a cancer analogue [227]. The self-replicating machine concept has enormous implications for interstellar exploration [228] and the search for extraterrestrial intelligence [229,230]. It suggests that extraterrestrial intelligence does not exist [231,232,233].

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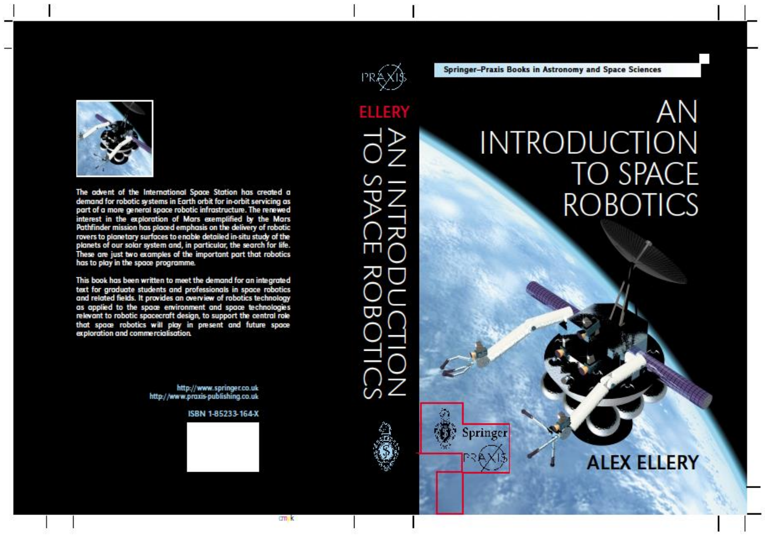
A. Ellery - *An Introduction to Space Robotics*, Praxis-Springer Publishers, UK, 2000 (662 pages)



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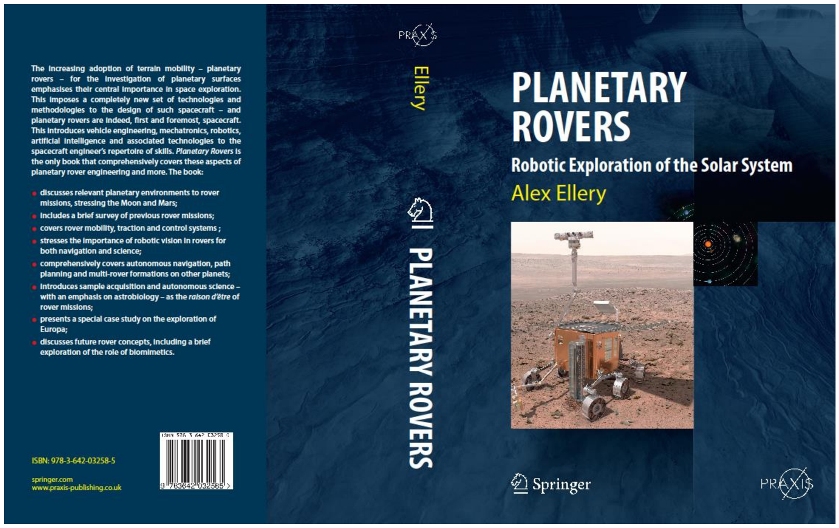

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2. "Alone – a Discovery Sourcebook for Astrobiology" (2003) *Int J Astrobiology* **2** (2)
3. "Life Everywhere – the Maverick Science of Astrobiology" (2003) *Int J Astrobiology* **2** (4)
4. "Life in the Universe" by Bennett J, Shostak S & Jakosky B (2003) *Int J Astrobiology* **2** (4)
5. "Children of the Stars: our Origin, Evolution and Destiny" by Altschuler D (2004) *Int J Astrobiology* **3** (1)
6. "Life & Death of Planet Earth: How the New Science of Astrobiology charts the Ultimate Fate of our World" by Ward P & Brownlee D (2004) *Int J Astrobiology* **3** (4)
7. "Life in the Solar System and Beyond" by Jones B (2004) *Int J Astrobiology* **3** (1)
8. "Rare Earth – Why Complex Life is Uncommon in the Universe" by Ward P & Brownlee D (2004) *Int J Astrobiology* **3** (1)
9. "Where is Everybody: Fifty Solutions to the Fermi Paradox and the Problem of Extraterrestrial Life" by Webb S (2004) *Int J Astrobiology* **3** (1)
10. "Between Necessity & Probability: Searching for the Definition and Origin of Life" by Popa R (2007) *Int J Astrobiology* **6** (2)
11. "Intelligent Life in the Universe: From Common Origins to the Future of Humanity" by Ulmschneider P (2007) *Int J Astrobiology* **6** (2)
12. "Life in the Universe: Expectations & Constraints" by Schultze-Makuch D & Irwin L (2007) *Int J Astrobiology* **6** (2)