IAC-11-B4.3.1

CROWDSOURCING SPACE EXPLORATION WITH SPACECRAFT-ON-DEMAND

Mr. Michael Johnson
JA, Oxford, United Kingdom, michael@johnsons.li

Ms. Sara Spangelo
University of Michigan, Ann Arbor, United States, saracs@umich.edu

Conventional methodologies do not scale to support the development of more than the few dozen spacecraft missions launched every year. We propose a new approach: a crowdsourced integrated system permitting the rapid development, deployment and operation of millions of small missions by explorers ranging from expert scientists and engineers to non-expert members of the public. Crowdsourcing, as demonstrated by Galaxy Zoo and StarDust@Home, is a powerful method of outsourcing tasks to a large amateur community.

Multiple small spacecraft result in economies of scale, redundancy and agility as recognized by projects such as NPSCuL and QB50. Community participation in space exploration allows orders of magnitude more missions and generates excitement about space, science, and technology in classrooms and living rooms worldwide.

Our web based system will allow explorers to select mission goals, constraints, and preferences. It will analyse these choices and suggest mission profiles and spacecraft designs, allowing explorers to trade-off design time, cost, capability, and performance. Interaction ranges from completely automated to extremely hands-on. It draws upon a library (designed and rated by explorers for utility, reputation, and quality) of open source, often reconfigurable, spacecraft components, subsystems, and mission architectures. Proven existing tools model, simulate and optimize the various subsystems. A concurrent design philosophy allows selection of appropriate spacecraft and mission configurations by iterating between subsystem optima while capturing whole system interactions.

To address the problem of building and deploying large numbers of small satellites, we propose producing and deploying spacecraft with Prepositioned Orbiting 3D Printers (POPs) such as our 2U CubeLab POP under development. Initial POPs (derived from existing extrusion 3D printers, wire-wrapping and pick-and-place machines) build spacecraft using replaceable ICES cartridges containing extrudable Insulator, Conducting wire, battery/solar cell Energy modules and Semiconductor modules borrowed from existing CubeSat and myPocketQub projects.

We describe architecture and prototypes of automated systems for operating the spacecraft, built for use by anyone. Tracking, telemetry, control, and payload data is transferred by communication networks consisting of spacecraft and ground stations, and allow reconfigurable parts such as FPGAs, memory metals, and software to be updated in-flight, permitting many explorers to share the same spacecraft for different missions. Social and legal structures necessary to manage such spacecraft are also addressed. Crowdsourced robotic space exploration could dramatically alter the pace and economics of space research. A Spacecraft-on-Demand system demonstrating scalable production of spacecraft on-orbit is expected to be operational in 2012.

I. PROBLEM

Space exploration missions are rare undertakings. Even including small satellites and CubeSats, only a few dozen are launched every year. Rovers and landers are even rarer and are fortunate if they manage to explore more than a few hundred meters from their landing site. If we wish to thoroughly robotically explore all the potentially interesting bodies in the solar system, large and small, on scale similar to the hundreds of thousands of human explorers who characterised the Earth during the great ages of discovery, a method of designing, building, deploying and operating millions of robotic exploration vehicles is needed.

Conventional design, assembly, integration, verification and testing methodologies for spacecraft large and small are very effective, but also extremely labour intensive, proprietary and are driven top down by large, fairly slow moving organisations. This usually leads to one off specialised designs or very occasionally single or double digit production runs. In addition, they are generally manually operated (albeit with automated assistance) by a very small cadre of highly trained mission controllers and systems operators. If we are to successfully explore huge numbers of scientifically interesting destinations an alternative approach is needed.

II. A POSSIBLE SOLUTION

We propose crowdsourcing space exploration to members of the public, automating as much of the process as possible and allowing the process to be driven from the bottom up as well as the top down.

II.I. Crowdsourcing

Crowdsourcing is a powerful method of outsourcing complicated technical tasks to a large amateur population and has been used to great effect in various fields including amateurs using web browsers to assist astronomers classifying galaxies and searching for exoplanets (Zooniverse projects), personal computer screensavers helping SETI researchers looking for candidate SETI signals (SETI@Home) and game console owners working with biologists to understand protein folding (Folding@Home). These efforts have harnessed vast networks of amateurs to perform manual tasks that only a human can do, for example, more than 450,000 people are registered to work on Zooniverse projects, or to provide resources that research groups would simply be unable to afford - the PlayStation2 based Folding@Home virtual supercomputer would comfortably sit in the list of the top 500 supercomputers in the world if it existed as a single physical machine. These examples show that members of the public are very open and able to help with tasks that at first glance would seem unlikely subjects for mass participation.

Community participation in space exploration would allow many orders of magnitude more missions to be performed. By creating sufficient economies of scale to make it worthwhile to automate almost every element of mission design and execution, professionals could be released from what are often fairly mechanical and mundane tasks in order to concentrate on devising standardised or automated solutions that allow their expertise to be applied to many missions instead of a few. Members of the public have shown that they are very willing to financially support efforts that interest them in the form of cash donations, donations in kind of equipment (for example, CPU cycles) and donation of labour. The donation of labour (technical and non-technical) for appropriate tasks can free up professionals to optimise and improve the quality of the tools for the whole community and so a virtuous cycle is created.

Crowdsourcing creates a sense of involvement through hands-on involvement in real science projects and generates excitement about space, science, and technology in classrooms and living rooms worldwide.

II.II. Shrinking, fractionating and swarm missions

Although there are many space exploration missions that can only be performed by large, expensive spacecraft, there are many that are suitable to being fractionated and implemented as swarms of small, inexpensive systems. Atmospheric science, distributed sensor networks, even certain types of imaging tasks can benefit from swarms of small satellites and are some of the applications driving the increasing numbers of CubeSat missions that were once seen solely as the preserve of 'big' missions. In addition smaller swarms of satellites bring with them benefits of economies of scale as the non-recurring engineering costs of their common subsystems are distributed across many spacecraft. One can also consider using less expensive solutions if one hundred per cent reliability is not an absolute requirement for mission success. If one has multiple spacecraft that can successfully perform a mission even if a percentage of them fail to operate correctly, then it is no longer necessary to spend the vast amount of time and money required to ensure that a single expensive spacecraft works first time, every time. Finally, by splitting a mission up into many parts, agility is gained through the parallelisation of many processes and the ability, if the system is designed to support it, to reconfigure the mission to respond to new circumstances. These benefits are being recognised by both civilian and military projects such as QB50 and NPSCul efforts.

III. SPACECRAFT-ON-DEMAND SOFTWARE

The users of our system first encounter the Design Centre software. This is web based to ensure maximum compatibility with the wide range of consumer and professional computing devices installed worldwide. It allows explorers to select mission goals, constraints and preferences, either from existing mission designs that traditional mission planning groups devise, or from designs originating from amateur groups or indeed the users themselves.

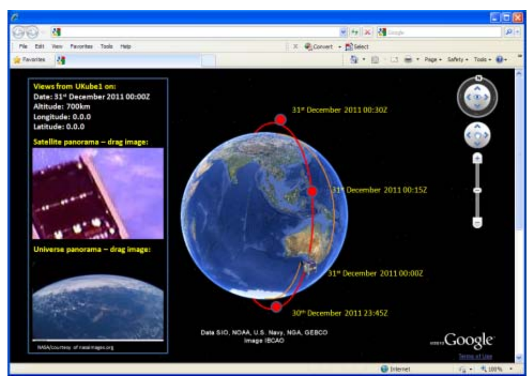


Fig. 1: User friendly preview of a crowdsourced mission design in the Design Centre web interface.

The software has several styles of user interface which, while interacting with the same underlying software, look radically different to end users. Amateur users more towards the consumer end of the consumer-professional spectrum are most likely to use the web, touch and 'sofa friendly' interfaces designed for use in a domestic environment. These simplify the process of mission design and operation to the point that a complete viable mission can be entirely specified by selecting answers to multiple choice questions and dragging and dropping predefined parts onto a limited selection of attachment points. Users at the professional end of the spectrum will have access to more powerful tools that use traditional graphical user interface and command line interfaces that while powerful and indeed necessary for these professionals to get the most out of the system, would be impossible for the vast majority of users to master.

Whichever interface is used, the underlying system allows explorers to select mission goals, constraints, and preferences. Interaction ranges from completely automated to extremely hands-on. The system analyses the users' choices and suggests mission profiles and spacecraft designs, allowing explorers to trade-off design time, cost, capability, and performance. These can range from as being as simple as preventing a consumer from attempting to deploy a multibillion dollar mission when there budget is just a few hundred dollars, to as subtle as showing the bit rate / power budget trade-offs that certain power subsystem choices might require. Although the vast majority of users will never need to understand or modify how these trade-offs are made, there is a facility for the professionals to review and, if necessary, revise the underlying models.

A key point of this system is that it draws upon a library (designed and rated by explorers for utility, reputation, and quality) of open source, often reconfigurable, spacecraft components, subsystems, and mission architectures. Allowing explorers to rate the utility of the part, the reputation of the design and the quality of the implementation allows feedback on all these vital properties to be fed back into the system so that future choice can be made with greater confidence.

The library describes all elements of a mission in an open source open access XML format that encapsulates all the various properties of spacecraft systems in a single format. For example, computer aided design files, source code, schematics, bit streams and other such elements are all encapsulated in a single file that is understood by all elements of the system. Where possible, open or de-facto industry standard formats are used and simply embedded in the XML allowing a large number of existing components to be swiftly integrated into the library with minimum effort.

Where library objects are defined from scratch, a parametric modelling approach is preferred to allow the maximum flexibility for both the design/optimisation phase and the production phase. For example, whereas a traditional computer aided design library might have separate, hand designed models for a 144MHz and 440MHz dipole antenna, the Spacecraft-on-Demand library part has a single parametric model 'dipole' whose properties (in this case, for example, the length of the dipole) would vary depending on the both the application inputs (for example, the frequency it is require to operate at) and the production inputs (for example, the dielectric constant of the insulator used to space the two halves of the dipole). Although much harder to design initially, this approach pays off dramatically when one wishes to use the part in vast numbers of custom designs and on a variety of production platforms.

Absorptance
Autoignition temperature
Breakdown voltage in vacuum
Coefficient of friction (like on like)
Coefficient of thermal expansion
Compressive strength
Critical temperature
Critical pressure
Curie temperature
Decomposition temperature
Deflection Temperature Under Load (0.45 MPa)
Density
Dielectric constant
Dielectric strength
Ductile-brittle transition temperature
Elastic limit
Elastic modulus
Electrical conductivity
Electrical resistivity
Elongation at break
Flexural modulus
Flexural strength
Fracture toughness
Heat of fusion
Glass transition temperature
Hardness Shore A
Magnetic susceptibility
Melting point
Modulus of Elasticity
Notched Izod Impact
Permeability
Permittivity
Poisson's ratio
Pouring temperature
Reflectivity
Refractive index
Seebeck coefficient
Shear modulus
Tensile strength
Tensile tear resistance
Thermal conductivity
Transmittance
Ultimate strength
Vicat softening point
Volumetric thermal expansion coefficient
Yield Stress
Young's modulus

Fig. 2: Materials properties used by parametric library components to calculate their optimal size.

To optimise and verify the designs that are assembled by the users and the parametric design tools, proven existing tools model, simulate and optimize the various subsystems. These can range from antenna modelling packages such as ENZEC through to complete mission design and analysis toolkits such as AGI's STK. Unlike the library of parts which encourages the design of custom parts specifically designed for the project, the optimisation and verification stage deliberate tries to avoid implementing any such techniques itself, instead limiting its role to managing interactions between as many third party tools as possible by working with established application programming interfaces. The focus on this part of the system is to try and utilise the many decades of experience already encapsulated in these tools by supporting as many as possible so they can all be used as drop in elements of the system and perhaps verify and validate each other.

This approach allows a concurrent design philosophy to be used to allow selection of appropriate spacecraft and mission configurations by iterating between subsystem optima while capturing whole system interactions. These interactions occur not just within the design of the spacecraft and mission, but also with the production processes due to their somewhat unusual, yet immensely powerful, nature.

IV. SPACECRAFT-ON-DEMAND HARDWARE

To address the problem of building and deploying very large numbers of small spacecraft of differing design, we propose producing and deploying spacecraft with Prepositioned Orbiting 3D Printers (POPs).

POPs allow designs prepared and optimised in a standard format by the Design Studio software on the ground to be uploaded, printed and deployed in space. POPs are best situated in locations that serve as useful starting points for multiple missions. For example, for short lived low Earth orbit (LEO) missions, one might position a POP on the outside of the International Space Station (ISS). For more ambitious missions, printers could be stationed in geostationary transfer orbit (GTO), low lunar orbit (LLO) or at suitable Legrange points throughout the solar system. One great advantage of prepositioning printers is that it allows the time for a spacecraft configuration to be tried in a specific location to be reduced to just the time it takes to upload the design to the printer and print it (typically a total of a few hours), rather than the months or even years it might take to physically send a new spacecraft to an existing location. A printer prepositioned in-orbit or on the surface of Mars could, for example, deploy new spacecraft in a couple of hours instead of the many months it currently takes even excluding the time it currently takes to build the spacecraft.

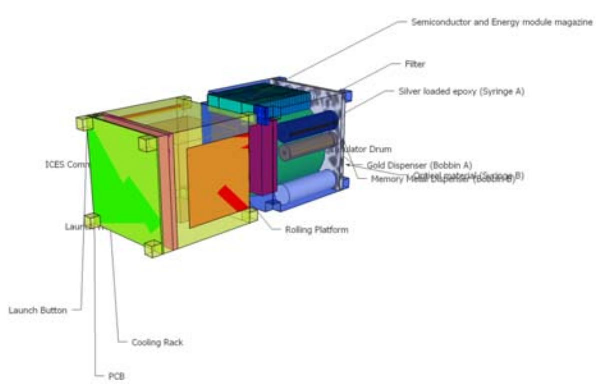


Fig. 3: A 1U POP and 1U ICES cartridge configuration

Initial POPs are derived from existing extrusion 3D printers, wire-wrapping and pick-and-place machines and are based on open source hardware whenever possible. Although the nature of the concept suggests that bigger is better when it comes to the size of POPs to allow the largest possible structures to be built, in order to allow inexpensive development flight testing of the concept, the first hardware has been designed around the CubeSat and NanoLab standards and are thus very compact – just 100mm x 100mm x 100mm (1U) each for the first printer and cartridge units. Although compact, a substantial percentage of the volume of the printer is available as print volume – approximately 70mm x 70mm x 70mm in the first designs.

POPs use replaceable ICES cartridges containing extrudable Insulator, Conducting wire, battery/solar cell Energy modules and Semiconductor modules. A variety of different materials are in the process of being evaluated for suitability as ICES cartridge materials with the ability to use the same material for multiple functions being important. Initial candidate materials need to be compatible with safety requirements of the environments where they are being tested which currently include on the bench, on parabolic flights and inside the ISS. In addition, we wanted to test a variety of different mechanisms for dispensing materials and so our first prototypes use a mixture of thermoplastic extrusion, paste dispensing, wire wrapping and module selection and placement.

The POP and the ICES elements are designed to be separate elements with the ICES cartridge being replaceable. The POP has been designed to be as generic as possible and so makes as few assumptions about the materials it will be dispensing as possible to allow radically different ICES cartridges to be used by the same POP. Our first POP consists of a Cartesian robot based on the open source RepRap 3D printer project moving a print head throughout the print volume. The print head consists of a thermoplastic extrusion mechanism (also based on the RepRap design), a wire wrapping mechanism, ports for accepting pastes or fluids for deposition and a mechanism for picking and placing 16mm x 16mm x <4mm and 16mm x 32mm x <4mm electronics modules.

The initial ICES cartridge contains a Kapton build belt platform derived from the MakerBot automated build platform onto which the printer prints. The cartridge materials are fed to the print mechanisms via a 16mm x 80mm materials port which is designed to be a standard interface between all POPs and ICES allowing the design of either to radically change while still maintaining compatibility.

The first cartridge contains an 80mm drum of 1.75mm PLA as its Insulator material which is fed through the materials port via an aperture in a standardised location to the POP thermoplastic extrusion mechanism. The drum is driven from within the cartridge by a very small stepper motor and holds a total of 200,000 mm^3 of PLA.

Up to three Conductors are supported in the first cartridge. The first is EPO-TEK H20K, a silver loaded epoxy commonly used in space applications. It is held in a 400mm^3 double syringe in the cartridge driven by a Fab@Home syringe driver mechanism. The material is delivered from the syringe via a standard aperture in the materials port by thin tubing to a needle tip at the print head. The second conductor is gold bonding wire (commonly used in the semiconductor industry) which is stored on a stepper motor driven 10mm bobbin containing 15m of 30um gold bonding wire. This is delivered within a fine tube to the materials port where it is passed on to the wire wrap mechanism. A second 10mm bobbin is provided to allow a third conductor to be supported at a future date and may be used for a memory metal.

Energy modules consist of a pair of Spectrolab TASC cells bonded to Thinergy MEC220 batteries and a small power control circuit. These modules are 16mm x 32mm x 2mm and are held in a single spring loaded stack containing forty of them in a predefined area of the materials port for picking and placing by the POP. Each module has a four wire connection consisting of positive supply, ground, I2C data and I2C clock which are brought out, one connection per corner, to allow the modules to be stacked and interconnected.

Semiconductors modules are derived from the Qubduino element of the myPocketQub project and consist of a Texas Instruments MSP430 with RF core, a Xilinx Spartan 6 field programmable gate array, 4GB of flash memory, power control and various embedded sensors. These modules are 16mm x 16mm x 4mm each and are held in two spring loaded stacks, each containing twenty modules in predefined areas of the materials port for selection and placement by the POP pick and place mechanism.

Future versions of the ICES cartridges are being designed that will include additional materials suitable for use as Fuel, Memory metal and Optical elements to increase the capabilities of the spacecraft that could be printed.

V. IMPLEMENTATIONS

Although the first version of the POP and ICES cartridges are small and crude, they do allow a surprising variety and number of spacecraft to be built.

For the purpose of comparison, a simple minimal spacecraft has been defined that consists of a single energy module connected to a single semiconductor module attached to a 35mm dipole antenna for communications. This simple spacecraft requires 3904mm^3 of insulator material to connect and support one of each modules, 375mm of conducting wire to form the dipole and provide the electrical connections between the modules and 8mm^3 of conducting epoxy to make the electrical connections between modules and wire. A single 1U ICES cartridge is able to print forty of these minimum spacecraft and still have a significant amount of its insulator and conductor materials remaining.

Printing spacecraft in space offers great scope for reducing the amount of material that needs to be launched into orbit per spacecraft as printed spacecraft do not have to be able to survive launch forces and thus can be designed to be gossamer like with little regard for the consequences of such a design choice during the launch phase. In addition, as materials cartridges do not have to worry about thermal dissipation during operation unlike finished spacecraft, for a given volume, we have observed that materials cartridges will be significantly denser than a finished CubeSat. All other factors being equal, we would expect to be able to print approximately 10U of CubeSat like capability from 1U of launch capacity if launching materials cartridges rather than finished CubeSats.

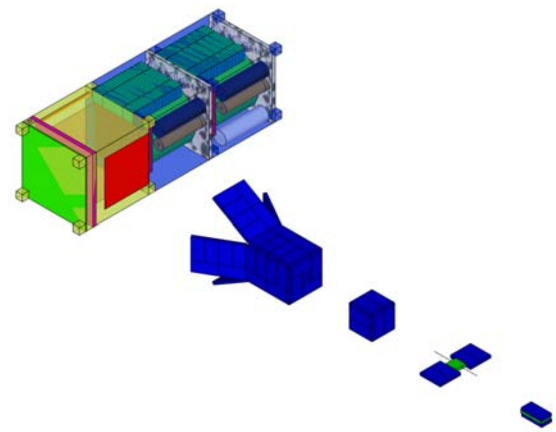


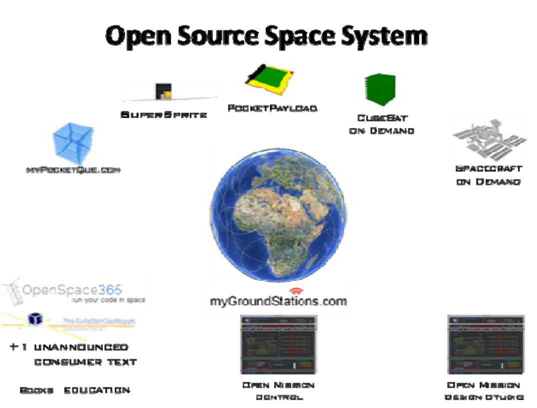
Fig. 4: Example spacecraft configurations that can be printed by a 1U POP and 2U ICES cartridge.

Although the minimum spacecraft is a tool to allow comparison of the capability of different sized cartridges, it is still a fully functioning spacecraft able to perform useful scientific missions.

The maximum volume spacecraft that a POP can print is greater than its internal build volume. The cartridge build platform is a Kapton conveyer belt which, in the CubeSat and NanoLab implementations, is aligned with two 70mm x 70mm doors in the side of the printer. This mechanism is normally used as a static build bed which is then run at high speed at the end of the build to eject the finished spacecraft out of one of the POP launch doors along a known vector. However, if parts are initially built attached to no more than a 30mm wide patch in the centre of the build belt, the belt can slowly be moved to one extreme or the other to allow structures greater than the internal build volume of the printer to be built. In addition, deployable panels can be printed that are stowed within the build volume but are deployed when the spacecraft is deployed from the build belt. Using techniques such as this, a single 1U POP attached to a 1U ICES cartridge can build, for example, solar arrays with a surface area of 20,480mm^2

despite only having a build belt with a surface area of 4,900mm^2.

These printed spacecraft are currently designed to use a very lightweight software system originally designed for myPocketQub femto-satellites (46mm x 46mm x 46mm, 125g). The semiconductor modules are preprogrammed with smart bootloaders developed for the myPocketQub project that include just enough functionality in an unconfigured state that as they are printed or after the printed spacecraft is launched, they are able to receive software and firmware updates over the air (current using amateur radio satellite service frequencies in the 2m and 70cm bands) and update themselves. These updates are most easily transmitted by the POP during the printing process as only a low power transceiver is required within the printer. However the process can also be performed from the ground using traditional amateur radio ground station hardware and software and print spacecraft and also update nearby peers if they are able to close the link. Using this mechanism, operating systems, flight software, field programmable gate array bitstreams and memory metal configurations can all be updated during the printing process to give the printed spacecraft specific functionality either at the end of the print process or as it is underway. These smart bootloaders are always present, so later in a mission the spacecraft can be updated or indeed completely reconfigured for a completely different mission, if necessary.



Fig, 5: Elements of the Open Source Space System from which much of the Spacecraft-on-Demand open source flight software and hardware is drawn.

A full description of the myPocketQub flight software package is beyond the scope of this paper, but it permits fully autonomous operation of spacecraft with infrequent contact with ground segment assets or other spacecraft running the same software. It is compatible with lightweight implementations of CCSDS protocols such as CFDP, allowing amateur and professional Deep Space Network assets to be used for communication and relay. All the software is open source and can be used, modified and improved by anyone.

In a crowdsourcing application, we would expect the vast majority of users to use the software unmodified as is and use the open source ground control software element (Open Mission Control) of the Open Source Space System wrapped inside a web interface to monitor and control their spacecraft. However the system is designed to be used by anyone for anything so we would expect competing software and communications architectures to emerge, hopefully maintaining compatibility with each other.

Fig. 6: Open Mission Control screenshot

The legal and social issues raised by the existence of such spacecraft also need to be considered. For example, what is the nationality of a spacecraft designed by a Canadian child living in Britain given as a gift to an Australian relative who lives in New Zealand printed on a Isle of Man registered POP using an American sourced ICES cartridge? If millions of spacecraft are exploring the solar system owned and operated by a similar number of users, a significant percentage will become abandoned and unwanted by their owners either through loss of interest, illness, death or other significant life events. We suggest that an important element of an integrated Spacecraft-on-Demand system is addressing such issues and that formal systems allowing the adoption of such spacecraft by individuals and/or states should be in place so that any discoveries that such spacecraft make are not lost.

VI. FUTURE WORK

The Spacecraft-on-Demand system is still at a very early stage. Prototype software is not very integrated or user friendly at this time and significant work is underway to resolve this.

Prototype hardware is on the bench and is about to proceed to parabolic flight tests in November 2011 and to an on-orbit test in a NanoRack on the ISS in 2012. It is intended that these experiments will demonstrate very simple yet complete end to end operation of the system in environments where humans are available to assist with debugging any problems – a printer jam in space is a problematic scenario most easily resolved by human intervention. If these tests prove successful, it is intended that the first free flying POP will be a 3U CubeSat launched to GTO in 2013.

Although starting out as a CubeSat / nanosatellite scale technology for cost reasons, there are no fundamental reasons why the concept cannot be scaled up to larger scale spacecraft and small satellite scale missions are already being informally discussed.

Improvements to all the materials in the ICES cartridges are currently underway as we understand better how they are used and what ideal properties they should have. Direct manipulation of semiconductor substrates utilising the natural environment of space is expected to be a significant future research direction.

VII. CONCLUSIONS

Crowdsourced robotic space exploration could dramatically alter the pace and economics of space research. By greatly increasing the number of missions that can be performed, the speed at which they can be assembled and the time it takes to launch and deploy them, this concept could be an extremely disruptive technology.

There will be benefits and drawbacks to opening up the exploration of space to anyone who is interested that will have to be carefully managed. The potential for whole scale pollution of space with frivolous spacecraft is a danger, but it is also an opportunity for an unprecedented explosion in the rate at which knowledge about our universe can be accumulated and perhaps even the beginning of the personal space age.

ACKNOWLEDGEMENTS

This work is a JA initiative sponsored by JA through unrestricted educational grants and the European Space Agency through its Summer of Code in Space program. Support in kind has also been received from ESATAN-TMS, Qioptiq, Zero-G Corporation and others. We would like to thank Adrian Bowyer, James Cutler, Nadeem Gabanni and Mason Peck for their valuable input.