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LEARNING TO FOLLOW: EMBRACING COMMERCIAL TECHNOLOGIES AND OPEN SOURCE FOR SPACE MISSIONS

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A large proportion of the space industry is moribund with long development cycles, high, rising (or at best stagnant) costs, and an extreme aversion to risk. Meanwhile, other industries such as consumer electronics see development cycles between 3-6 months, exponentially lowering costs per unit capability and a more lenient attitude towards risk. Why aren't these trends seen more widely in the space industry? Based on our experience with the NASA "PhoneSat 1.0" mission and the joint SSTL and Surrey Space Centre "STRaND-1" mission, we explore the possibilities that arise by adopting and exploiting innovations from outside industries. The smartphone technology central to both our efforts is a good example, with the smartphone industry investing billions of dollars to produce robust, tightly packaged devices with very high levels of capability. Using this technology as-is offers many benefits for space applications. These include leveraging widespread open source software, the opportunity for extreme rapid prototyping, and faster, cheaper missions with potentially higher capability. Significantly, this approach dictates a new paradigm with different rules where the large consumer electronics industry leads and the space sector follows. There is room for greater risk tolerance, spacecraft can be disposable (while still being mindful of debris issues). They can be designed, built and be flight ready on very tight timescales (days or weeks), and also launched in great quantities (hundreds, thousands), offering technological and responsive capabilities not feasible today. They integrate more advanced multi-core technologies. The fast iteration time-scales of the hardware coupled with open source software and open hardware platforms also allow for rapid prototyping and testing of spaceflight software. The capability for fast release cycles is something not typically seen in space-flight software. Smartphones in particular offer standardized platforms for software development, as well as very large communities of talented programmers. This allows the focus of innovation to ultimately shift away from the hardware, and further into the software and information technology domains. The open source aspects of our efforts also open up the opportunity for many people to undertake their own space exploration, from school students to hobbyists. While CubeSats and other opportunities have been possible for some time, it is only through this approach that we are capable of easily producing high-capability spacecraft within the means of ordinary people. This means that their efforts are also meaningful, and could provide valuable contributions to science and human well being on Earth.

I. INTRODUCTION

This paper discusses the potential for using low-cost, modern electronics in spacecraft, thereby breaking the vicious cycle of "designing for space", "space qualification" and providing the benefits of tracking the bleeding edge of technology. It is a high-level and non technical account. We present based on our experiences and in particular the of our respective spacecraft projects, STRaND-1 mission[*] being developed by Surrey Satellite Technology Ltd (SSTL) and Surrey Space Centre (SSC) at the University of Surrey in the

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[*] C. P. Bridges, S. Kenyon, C. I. Underwood, M. N. Sweeting, "STRaND: Surrey Training Research and Nanosatellite Demonstrator", 1st IAA Conference on University Satellite Missions and CubeSat Workshop, 24-29 January 2011, Rome, Italy

United Kingdom, and the PhoneSat Project[†] being developed by NASA Ames Research Center in the United States. Both projects started independently but both are attempting to use an Android-powered[‡] smartphone as an element of the spacecraft avionics. In the case the PhoneSat project, the smartphone is the entire spacecraft flight computer and and avionics and in the case of STRaND it is a supplemental payload -- and there are advantages and disadvantages to each approach. However, with this general direction, both projects are attempting to leverage the billions of dollars invested in the minaturization of computer processing and Micro-electro-mechanical Systems (MEMS) sensors inside a modern smart phone, thereby allowing ultra-cheap, high capability spacecraft to be built with minimal effort.

NASA Phonesat

PhoneSat is a project initiated at the NASA Ames Research Center in early 2009, to investigate whether Commercial off-the-shelf (COTS) hardware, and in particular a smartphone, can be used as the basis of a capable and ultra low-cost bus. The Nexus One smartphone used provides the core functionally of PhoneSat 1.0, which utilizes the phone's integrated 1 GHz processor, 500 MB of RAM, 16 GB SD card, 5 Megapixel camera, 3-axis accelerometer, 3-axis magnetometer, and the open-source Android operating system. With the use of a single phone, the PhoneSat project hopes to demonstrate that the entire core componentry of a spacecraft can be purchased for under US$5,000. The PhoneSat project hopes to launch the first of these spacecraft in late 2011.

The STRaND Mission

STRaND stands for Surrey Training, Research and Nanosatellite Demonstration, and the aims of the programme are synonymous with the acronym. The programme was initiated to give less-experienced engineers and researchers the chance to gain new skills, develop new, innovative nanosatellite technologies with the possibility of commercialisation by SSTL, challenge the traditional SSTL approach and the processes that have developed in SSTL over the last 25 years, and perhaps most importantly to maintain the formal and informal links between SSTL and SSC at all levels of both organisations. The STRaND Nexus One is considered one of many payloads on a typical 3U CubeSat along with other COTS components. The first satellite, STRaND-1, has a 40 MHz ARM7 on-board computer which control attitude and orbit control software (AOCS), nano-magnetorquer rods, nano-reaction wheels, pulsed-plasma thrusters (PPTs), GPS receiver, butane thruster, 155 MHz ARM9 computer which runs a real-time Linux kernel, and the Nexus One smartphone payload.

Dilemma: why has this not been done to date?

If there are such obvious advantages of using consumer electronics over traditional space electronics – in terms of basic price performance metric – then why has this not been done to date? This is the dilemma. There are three major thrusts that may explain this dilemma:

1. Risk Aversion. The space sector has too much inertia to jump to such a radical new solution space with no qualification in the harsh environment of space.
2. Technological Maturity. Integrated devices with the necessary technologies are only just coming-of-age.
3. No need. Some parts of the space sector just do not need more advanced processors and sensors.

But in addition, there is evidence to suggest that the dilemma as stated is not correct; it is starting to break:

4. Our efforts in this direction are not completely isolated or new; in fact others are pursuing this vector. [§]

Our conclusion is that this is an idea whose time has come, and it rapidly is garnering increasing interest from various groups around the world. We shall address each of these issues below.

II. RISK AVERSION IN SPACE ACTIVITIES

For decades the space sector has built up more and more risk aversion. This is true in military, civil and commercial space sectors and globally. In the case of NASA, risk is typically mitigated through additional engineering. The public visibility of NASA's activities and the perception of wasted taxpayer funds put NASA in a situation where any failure is a public relations nightmare, and so staggeringly expensive engineering is

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[†] M. Safyan et al, "PhoneSat: a smartphone-based spacecraft bus", International Astronautical Congress, Cape Town, South Africa, October 2011, IAC-11-B4.6.B9 (10655)

[‡] Android Developers website http://developer.android.com/ accessed 13 Sept 2011

[§] For example for a list of similar activities see http://www.nasahackspace.org/cellphonessmartphones/ or various press e.g. "Mobile Phone to Blast into Orbit", http://www.bbc.co.uk/news/science-environment-12253228, BBC News 23rd January 2011, or "Ground Control to Major Smartphone? NASA Wants Phones to Pilot Spaceships", http://www.foxnews.com/scitech/2011/02/11/cell-phones-space-smartphone-nasa/, FoxNews 11th February 2011 exhausted in an attempt to almost totally eradicate risk on each mission.

Commercial industry typically is slightly more tolerant to risk, but not much more so. Industry manages risk with a combination of engineering, insurance and in some cases a measure of redundancy. Expensive insurance policies ensure that a second chance can be had in the event of a total failure. However, to reduce insurance premiums, engineering risk reduction is also required along similar lines to NASA. In addition, since governments remain the primary purchaser of space capabilities, companies are often beholden to the Government risk posture, and often adhere to it conservatively. Even the ‘real’ commercial side of the industry is also not immune to the "cannot fail mentality". Surrey Satellite Technology Limited, for example, has a perfect flight record having never lost a satellite in the history of the company. Surrey has a desire to maintain that record, and so a culture has evolved whereby the company arguably takes significantly less risks than they did at their founding 20 year ago. They make advances as technology from Surrey Space Centre matures and can be utilised in newer spacecraft. Other strategies such as trading risk for redundancy through multiple units or shifting to a paradigm of disposable units are essentially contrary to the postures of these entities.

Another significant component is the expense of launch, which causes a vicious cycle consisting of two parts. Firstly, rockets are fundamentally expensive. This was the case right from the start of the space age. This cost incentivised the satellite developers to optimise their designs very carefully for the mission.[††] Thus, the costs of the satellite go up to ensure that their probability of success is very high, and that they last a long time since the launch is expensive so doing it repeatedly is too dear.

The cost of the rocket goes up to ensure that it is has high enough reliability to not waste the great expenditure on the satellite. This has led to a situation where the typical rockets used by the US government and major commercial space sector costs have seen consistently rising costs despite widespread deflation being seen by other industries. The current situation is that launches now typically cost \$50-300m, and satellites typically cost \$200-600m.

The Challenge of Doing Something New

As mentioned, this cycle of spiralling costs is accompanied by considerable aversion to technical risk and a desire to eliminate it entirely. The main manifestation of this is the phenomenon of "space qualification", whereby satellite manufacturers essentially forbid the use of components that have not been proven to already work in space. Few organisations have risk-tolerant technology development programmes to specifically try out new technologies and methods, and thus we have a catch-22. Adoption of new techniques becomes extremely challenging in this environment. In addition, the timeframe for development of most satellites is 3-7 years from authority to proceed to launch, and so there is a further lag in the technologies that are incorporated into the design (often ‘frozen in’ to the design in the first year or two).

Adding the desire to only use flight proven technology, and the development timeframe, combine to result in satellites using components that tend to be 10-15 years behind the latest that is available. Most technologies in satellites are worse than obsolete when they launch when compared to technology readily available commercially. For example, the recent NASA Phoenix mission to Mars launched in 2008, had a 33MHz processor with 128 MB of RAM. This is in a day where commercially a CPU with 30x that speed and 10x the RAM can be readily purchased at low cost.

The state of the space sector thus described has a very high inertia toward established practices and known, safe technologies, and a corresponding resistance to new technologies. The whole space sector finds it hard to move away from the >\$100m satellite model. The idea of \$10k satellites is so far from their realm of thinking that most engineers currently in the space sector cannot even take it seriously, whilst those outside the sector somehow think that space is really hard and impenetrable (which historically it has been but may not be now).

III. TECHNOLOGICAL MATURITY: RECENT ADVANCES IN CONSUMER ELECTRONICS

We now turn to our second argument against the dilemma, asserting that integrated devices with the necessary technologies are only just coming of age. It is only in recent years that a large fraction of the technology needed for a satellite has become housed into a single small commercial device. Today’s smart cell phones, for example, have most of the core capabilities of a spacecraft, including a fast processor (in fact, faster than that in most spacecraft launched today) and large memory capacity; a range of sensors such as accelerometers, rate gyros, magnetometers (all useful for attitude control) and GPS (for position); batteries and power management; several radios; and high resolution cameras. Companies investing in them, such as Apple, Google, HTC, Nokia, Motorola, etc,

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[††] Note that early in the space age the spacecraft typically cost much less than the launch vehicle, today it is the reverse, such that the great expense of the rocket is not wasted on a spacecraft that didn't work.

have squeezed sophisticated capability into a small, physically robust form-factor, and mass-produced them, lowering the cost. They do lack some capabilities needed for a satellite for example solar panels, and a propulsion system; but remarkably the overlap with the basic feature list for a satellite is very high indeed. But this did not used to be the case: they have only gained these capabilities relatively recently. The first phone with a camera integrated was the Ericsson P800 in 2000; the first with a fast (300 MHz) processor was in 2004(?) with the Palm Treo; in 2007 came the first with GPS (Nokia N95) and with accelerometers (iPhone1); and in 2009 rate gyros (e.g. iPhone2).

So, in sum, it has literally only very recently been the case that one could buy a device with such sophistication and capabilities that it is close to that of a satellite bus (bar solar panels).

VI. NO NEED FOR FASTER PROCESSORS

But despite these recent developments, the space community are far from flying the latest technology and still aim to fly expensive, and often obsolete, slower devices; for a number of reasons. And one legitimate reason one can find is that there is no direct need or advantage for these particular technological advances. Take a commercial GEO telecommunications satellite as an example: the main payload is a bent pipe RF link, where the bulk of the data is not passed through any processor. Thus there is little to be gained for the payload to have a more advanced processor. Meanwhile the bus has adequate functionality with an old slow processor to do its job. And since the payload remains massive and expensive, and the cost of the launch is high, there is little to be gained in cost savings by going to new avionics system – the mass savings are minimal overall mass and the cost savings are minimal compared to the overall cost. Thus there are genuinely classes of space assets for which these technologies serve to do little to advance, at least on the face of it.

V. EMERGING INTEREST IN LOW-COST SPACECRAFT

Finally then, there is the counter argument to the dilemma: although no actor has implemented it to its full potential, several are pursuing it and more are joining.

The most obvious case already presented is that both SSC/SSTL and NASA conceived of their smartphone-based projects independently and within a short time of one another. Although taking a different approach, SSC, SSTL and NASA have similar motivations for going in this direction: commercial technology is now so good it is able to make satellites orders of magnitude cheaper. They have also both homed in on the very same smartphone -- the Google Nexus 1.

But these actors are far from alone: others have started small companies also on a similar direction, albeit at an early stage of development. These include Satellogic[‡‡], formed out of Singularity University, and Arkyd[§§], the founders of which we know personally. Limited online information says "Arkyd Inc., an aerospace startup applying disruptive technologies for the commercial robotic exploration of space". An additional list of phone-related activities can be found in the footnote[†††]. Finally, DARPA's System F6 (Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange) programme -- which seeks to "demonstrate the feasibility and benefits of a satellite architecture wherein the functionality of a traditional "monolithic" spacecraft is delivered by a cluster of wirelessly-interconnected modules capable of sharing their resources and utilizing resources found elsewhere in the cluster" -- is pursuing a similar direction of consumer electronics and redundant constellation systems with some of its investments[‡‡‡].

VI. THE DOWNSIDES

Of course there are some potential disadvantages of these electronics.

Radiation tolerance

The larger the device layout, the more immune it is against radiation effects such as total ionising dose (TID). Newer terrestrial devices, albeit optimised for power, may still consume as much due to the clock frequency. Additionally, if a single effect event (SEE) occurs where a high-energy particle passes through electronics, volatile memory areas such as SRAM or caches can become corrupt. Given the multi-layer device layout architectures of modern smartphones and the reduction in gate size, instead of a few corrupt locations, there could be a larger number of corrupt addresses. There are key challenges requiring research in high-density COTS devices to how their behaviours change in hostile environments before they are fully adopted by the space community.

[‡‡] Satellogic website: http://satellogic.com/#782/tumblr

[§§] Arkyd Website: http://arkyd.com/ & http://www.naymz.com/chris_lewicki_3472626

[†††] http://www.nasahackspace.org/cellphonessmartphones/

[‡‡‡] DARPA System F6 website: http://www.darpa.mil/Our_Work/TTO/Programs/Systemf6/System_F6.aspx

Mission Applicability

There are constraints limiting mission applicability. In the discussion so far, we have concerned ourselves with the applicability of consumer electronics to space missions in general. But if one focuses down to the areas where there are projects attempting to use them today, one notices that it is mainly in the domain of cubesats. As detailed elsewhere, the CubeSat form factor leads to various limitations. In particular, these platforms tend to be power and data rate limited and thus only a certain class of small, low lass, low power and low data rate payloads are tenable. For example large optics are not possible, or large power amplifiers for high throughput communications satellites are not possible. So these are not going to replace Hubble or a standard GEO telecommunications anytime soon.

Basically the advantages of consumer electronics are not applicable (at least currently) to all of the broad range of space missions – many of which are held back by the fact that core components are not undergoing similar advances in terms of price performance, size and cost. If a payload for a mission still requires 60W of power, is 100kg, costs $30m and needs little or no processing power – and there are no commercial electronics versions of these currently – then one cannot reap many of the benefits of the lower cost and more advanced processing found in consumer electronics for the satellite bus nor the advantages of moving to a smaller platform since the payload dictates otherwise.

On the other hand, a myriad of instruments do fit into this class, e.g. magnetometers and radios, retro reflectors and atomic clocks. A whole range of science missions can be done with such systems as well as operational capabilities. For example small platforms can do a large constellation heliophysics mission, or geodetic missions or even could create a cheaper global navigation system or a low bandwidth communications network. And where the missions can be done this way, there are considerable cost advantages. Moreover, many instruments are getting smaller, cheaper, less power, as well as becoming more readily available commercially at low cost. Thus with time also and so the number of missions that these satellites could do is increasing with time also.

VI. WHAT DOES “FOLLOWING” MEAN FOR THE SECTOR?

What are the lessons from these observations and research developments? What actions could those interested in this be approach embrace? Here are a few:

1. Take lead from other industries, enabling:
    a. Access to latest technologies
    b. Leverage their investments
    c. Stay on their development curves
    d. Ease of upgrade path
    e. No lock in - either from a given industry or vendor
2. Make use of public APIs, open standards,
    a. Favour open technologies with open standards
    b. Do not invent in space proprietary standards
3. Vendor agnostic – one can change to another supplier, or another design all together

All of these recommendations are already to some extent followed in the sector. For example, the use of COTS devices and modified Internet protocols is found on SSTL satellites. But not to the radical extent proposed in the PhoneSat and STRaND missions. The pros and cons of this approach ultimately end in a trade-off in a number of areas including cost, risk, capability, and security. Leveraging newer cutting-edge technologies will be cheaper and more capable at the price of higher probability of failure. Whilst more bespoke, proven, and expensive devices are lower probability of failure. When assessing these two processes in time, both have their own development cycle but terrestrial open-source technologies can leverage existing support/forums and developer experiences that bespoke space systems cannot.

VII. CONCLUSIONS

In conclusion, for space to learn to follow other industries will mean adopting open standards rather than inventing narrow-space only ones, and leveraging the latest technology as it becomes available. In our opinion, the risk will be higher but the rewards of tracking the high investment underlying phenomena of Moore’s law[§§§] will result in a huge net win for space actors taking this approach. Ultimately one can envision a situation where space may transform into a software dominant domain where rapid innovation in software dominates the advancement of the sector rather than hardware capabilities. Future research and exotic mission scenarios will soon be feasible as space accelerates its development and applications for exploring our world and solar system.

[§§§] Gordon E. Moore "Cramming more components onto integrated circuits". Electronics, Volume 38, Number 8, April 19, 1965.