A Realistic Dream – a Top-Down Feasibility Study for MEMS Planetary Exploration

R.M. Newman, E.I Gaura, J. Tabor and S. Mount

* School of Mathematical and Information Sciences, Coventry University, Coventry CV1 5FB, UK,
R.M.Newman@coventry.ac.uk

ABSTRACT

We present here a design study for a planetary exploration mission using a myriad of microsensors in place of the single probes used hitherto. The purpose of the study is both to provide an attractive scenario for the promotion of the importance of pervasive microsensing technologies and to inform a continuing research agenda in this area. Some useful general conclusions about the importance of high levels of node intelligence and autonomous, self-organizing systems can be drawn from the details of this scenario.

Keywords: Intelligent sensors, sensor arrays, formal specification, fault tolerance.

1 INTRODUCTION

As part of our work on pervasive sensor systems we have developed a scenario, mainly as a focus for motivating the importance of and potential of this technology. The field of operation of the scenario had to be sufficiently exciting to motivate and enthuse lay people, with no current stake in the technology. As a secondary objective, we wanted use the scenario to test out our ideas on pervasive sensor system construction, so it had to be sufficiently challenging as a technical exercise. We started this shortly after the failure of the Beagle II Mars mission. What we came up with was an alternative mission profile, based on the use of a host of MEMS based intelligent multi-sensor motes. As we developed the scenario, it became apparent that, at least in hardware terms, it was distinctly feasible using current technology. This paper provides a brief overview of the scenario, and makes the case for its feasibility.

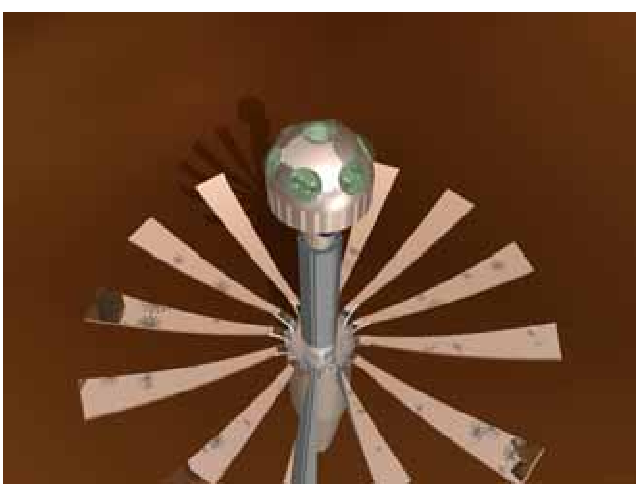

Figure 1: Daisy planted on the surface

2 THE MISSION

Instead of a single lander, a probe releases thousands of 'micro-landers', which together gain data from an area of the planet's surface. In this case, a micro-lander is called a 'daisy' (for Distributed Artificially Intelligent SensorY), and has some resemblance to an earthly daisy, being shaped like a flower with petals (which are actually an active optical antenna- see illustration in Figure 1). Not being planetary scientists, we have to make assumptions about the experiments to be carried. In the end, we have borrowed a few sensor types from recent planetary missions. The most interesting one, from a computational point of view, is the imaging part of the mission. Previous missions have placed cameras on 'rovers' which can be moved to explore a region in detail. The computational question posed is: can images gained from a field of sensors be pieced together to provide detailed visual information about locations within that area?

3 INITIAL DESIGN ASSUMPTIONS

The following initial design assumptions are made for the daisy:

- Optical communication. This is necessary to allow a sufficiently small antenna to fit within the 2cm size and allow communication to the host satellite. Given the predominantly red colouration of the planet, blue has been selected as the colour of the laser, to ensure maximum contrast against the background.
- Photo voltaic solar power generation.
- A sensor load of image, temperature, seismic (accelerometer), atmospheric pressure sensor, atmospheric composition sensor and magnetometer.
- Basic mote dimensions of 20mm by 7.5mm. This allows room for 5mm square chips to provide the basic functions for the device.

4 POWER BUDGET

The Martian solar irradiance at noon is 590W/m2 [1]. The outline design for the daisy envisages a 20 mm diameter solar collector with a fill-factor of 0.5. Thus the area of the solar collector is 0.000157 m2, and the power collected (at noon) is 93 mW. Allowing for night, and the variations of illumination over the day, we might expect an average value of just 1/10th of this, giving an averaged budget of 10mW. Spectrolab, Inc., has demonstrated conversion efficiency for a silicon photovoltaic cell of 36.9% [2]. Using the more efficient GaAs technology, an efficiency of 40% is not unreasonable. Our total electrical power budget is therefore 4mW.

5 COMMUNICATIONS POWER BUDGET

The most power hungry communication is likely to be with the host satellite. We can assume that the satellite will be equipped with a large and efficient optical antenna system. The required incident power is determined by the acceptable bit error rate (BER), the noise floor of the photodetector and the size of the reflector system. For a BER of 10^{-10} (as required by SONET) then the required signal to noise ratio is 12.732 [3]. The required optical modulation amplitude (OMA) is given by :

$\frac{i_n SNR}{\rho}$. i_n is the input referred noise figure for the front end amplifier, ρ is the responsivity flux of the photodetector. The average optical input power P_{AVG} is

$$\frac{OMA(r_e+1)}{2(r_e-1)},$$

where r_e is the 'extinction ratio' – i.e. the power ratio between a logic '0' and a logic '1'.

We can estimate this figure using figures for appropriate 'off the shelf' parts. A Centonics OSD1-5T has ρ = 0.2 A/W and a MAX3266 transconductance amplifier an i_{in} of 200nA. Thus, in this example the OMA is

$2\times10^{-7}\times12.732/0.2 = 12.732\mu W$.

P_{AVG} is $12.732\times5/6 = 10.6\ \mu W$, assuming an r_e of 4. Thus if we assume a 1 m^2 beam gathering reflector on the satellite, the daisy must be equipped to transmit a power of 10 μWm^{-2} at the orbital height of the satellite. The height of a geostationary orbit of Mars is 1.71×10^7 m.

The minimum beam angle for a 20mm radius reflector operating at a 405nm wavelength (as formed by the daisy petals) is $1.22\lambda / a = 1.22\times405\times10^{-9}/0.02 = 2.47\times10^{-5}$ rad. At the orbit height the beam diameter is 422m, its area around 140000m^2, and therefore the power required in the beam 1.4W. Assuming a laser diode efficiency of 20% [4], then 7W of input power is required for communication with the satellite. This power usage is sustainable within the overall package, but will obviously require to be used very sparingly. Hence the need for a clustered organisation of motes, whereby daisy to daisy communication is the norm. If we allocate ¼ of the power budget to such communications (1mW into the laser), then, assuming the same receiver sensitivity figures, and an effective receiver and transmitter area of 10^{-4} m^2, to allow for the fill factor and beam steering geometry, the required irradiation at the receiver is $10\times10^{-6}/10^{-4} = 10$ mW m^{-2} . The minimum beam angle is $1.22\times405\times10^{-9}/0.01 = 5\times10^{-5}$ rad. This gives a communications range from sensor to sensor of about 70m.

6 SUBSYSTEMS ON A CHIP

6.1 Power Generation and optical reception.

This subsystem uses a specialist process to achieve high levels of both photovoltaic efficiency and photo generation efficiency. It comprises the following:

Solar/communications collector.

Laser diode(s) for communication.

Blue and UV excitation diodes for spectrometers.

This chip will require to be fabricated using a suitable technology for blue laser diodes. These are currently exotic, requiring a silicon carbide substrate and InGaN technology. It is to be expected that large scale usage in 2nd generation DVD systems will bring this technology into the commodity arena. One advantage of the 'exotic' technology is that photovoltaic generators may be a little more efficient implemented in these technologies.

6.2 Atmospheric sensor

The chemical sensor in the head is to sense gas composition of the atmosphere. There are several designs for chemical noses, including a MEMS Fabry-Perot chemical sensor [5]. This is a particularly attractive option here, because of the proximity of a suitable excitation source from the optical chip. Also, the Fabry-Perot sensing mechanism will also allow simple integration of a

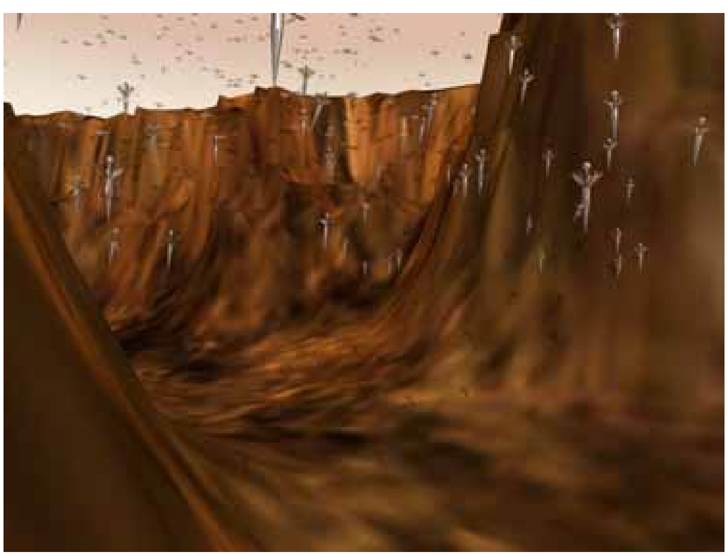

Figure 2: A cloud of sensors approaching the surface

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pressure sensor, as discussed above. From the stated source, each sensing dot is 200μm in diameter, allowing sufficient space for pressure and several gas specific detectors on a 5mm square chip.

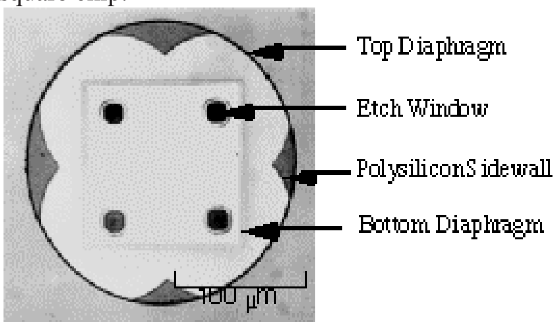

Figure 3: Fabry-Perot sensor dot (from [5])

The design of an atmospheric pressure sensor for Martian use is discussed by Reynolds et. al. [6], although this sensor provides for more extreme requirements than are needed here, since it is designed for a 100000g impact. For this application a fairly straightforward MEMS pressure sensor will be appropriate. Since the Fabry-Perot sensors discussed above have the ability to sense pressure (the pressure causing deflection of the sides of the interferometer cell), it would be possible to integrate the pressure sensor with the chemical sensor discussed above.

6.3 Magnetometer

Several magnetometers have been described in the literature. It would be advantageous if the magnetometer can be integrated, along with the chemical sensors and seismic detectors into a 'lab on a chip'. A mechanical MEMS magnetometer has been described by Moreland et. al. [7], and a similar device, with optical pick off (suitable for integration with the optical chip above) patented.[8]

6.4 Seismic detector

Many MEMS accelerometers have been described in the literature, and are available as commodity products. The interesting, and unusual, opportunity here is to use an accelerometer with optical pick off, to integrate with the optical chip discussed above.

6.5 Lab on a chip

If optical pick-off is used as discussed for the pressure sensor, accelerometer and magnetometer, then the optical chip can be extended to form a 'lab on a chip'. The available chip area is $2\times10^{-5}m^2$. There is room for around 500 Fabry-Perot sensing spots, as described above. Assuming that a suitable mechanical layer can be fabricated to provide proof masses for the accelerometers, and the magnetometer transducer(s), these can be provided by this one chip, while still allowing space for many discrete chemical sensors. The complete 'lab' could formed by a sandwich comprising the optical generation chip, the MEMS Fabry-Perot chip and a CMOS or CCD image sensor to sense the state of the FP dots. It is possible that this chip could be integrated with the image sensor chip.

6.6 Image sensor

This subsystem is straight forward, being a silicon CCD or CMOS image sensor. More complex are the mechanical arrangements, particularly if it is to double as pick-off for the Fabry-Perot lab on a chip. The resources that need to be integrated are a 500 pixel array for the pick-off and and image sensors for imaging the surroundings. The design goal is a 360% image circle. This can be provided with four 2000 pixel image patches and 90% image optics for each. This requires an 8500 pixel array, on a 5mm square chip, easily within current technological capabilities.

6.7 Control processor

The purpose of sketching out such a design is to allow resource decisions to be made about the scale and capability of the processor. The design proposed above essentially reduces all data collection to image processing (at least for the purposes of processing power estimation). Large amounts of data can be potentially collected, but with such expensive communication resources, substantial data reduction needs to take place.

As an example of the type of computation which might be made, we will consider briefly the computation of a terrain model based on stereo imaging from a sensor and its neighbour.

This will require exchange of 8000 pixel datasets, feature detection and correlation and 3-D model generation. The power budgets make it impracticable to transmit this data back to the satellite, so the computation must be performed locally. Thus, a capable processor, with a large memory space is required. As an example, a suitable processor core, the ARM7TDMI-S, implemented using a 0.13μm technology requires a die area of $0.32mm^2$, and has a power consumption of 0.11mW/MHz [9].

Since we have $25mm^2$ chip area available, the rest can be devoted to storage. FLASH densities (at 0.13μ) are 0.052×10^{-6} mm^2/bit [10].

SRAM densities are 2.43×10^{-6}mm2/bit [11]. Thus, there is room for 500Mbit flash or 10Mbit SRAM. Obviously, flash memory will form the bulk of the 'storage memory'. If we allocate 0.5Mbyte (4Mbit) RAM, then there is room for 37.5Mbyte flash, to provide program memory and longer term data storage. Looking at the power usage, allocating 2mW of our budget to the processing allows the processor to operate at an average rate of 18MHz.

6.8 Active antenna

The 'petals' of the daisy are supposed to form a beam steering reflector with a dual purpose, firstly of focussing incident solar radiation onto the photovoltaic/optical reception cell, secondly to steer both the outgoing and incoming laser beams. Also they have a role in controlling the descent of the mote, by altering the aerodynamic drag as it falls. Using the accelerometers it should be possible for the mote to navigate as it descends. The emitters and receivers are located in the head, firing downwards onto the reflector via a beam steering mirror. The shape of the reflector must be varied from a straightforward parabolic bowl, when the target is overhead, to a complex, reflex configuration when the target is on the same lateral plane. One possible technology is PVDF piezo film, which can certainly produce the scale of deflections required when used in a bimorph configuration [12]. Advantages are the simplicity of fabrication, the complex forms can be obtained by suitable patterning and intelligent control of the electrodes printed on the surface of a PVDF bimorph. Disadvantages include poor high temperature capability (135°C, which means the motes will need to be re-entry protected) and the requirement for high drive voltages. These will require a special high voltage controller chip, to which the petals will be bonded. This chip will double as the general power management for the mote.

6.9 Power storage

The bulk of the mass for the daisy needs to be at the front (in the spike) so that it is aerodynamically stable on descent, and falls point down. This mass is formed from the power storage battery, and will have a volume of 130 mm^2. Lithium ion cells have a power density of 300W-hours/l, so the capacity of this battery is 39mW/hours – at our 4 mW budget, enough to power the mote for 10 hours.

7 SYSTEM LEVEL CONSIDERATIONS

One of the nice aspects of this scenario is that it allows exploration and detailing of many of the systems design issues. For instance, the daisy has far higher processing capability then most current motes. The reason for this is partly prejudice (the designer has been caught out several times by 'under-processoring' designs, never by 'over-processoring' them) but can be justified by the details of the scenario. One of the major aims is to assemble images from many of the motes to make a visual model of the surface, allowing it to be explored as a rover would. However, given the cost of communication to the host satellite, it is not feasible for each daisy to transmit its own image data to it. Rather, clusters of daises must collaborate to reduce the data a single local models, which are then transmitted home. Thus the daises must be capable of undertaking complex image processing, requiring a large processor and memory. In any case, as we have seen the size and power budget of the processor is a small fraction of the overall budget, using a tiny processor would gain little and lose much in terms of capability. Another consideration is software construction. A capable processor simplifies this process considerably, essential as the software required will be sophisticated and complex to develop.

8 CONCLUSION

Although initially simply a 'blue sky' exercise, we have seen that in hardware terms at least the daisy is a practical proposition. The sensor motes used are relatively simple, mechanically, and most of the required technology has already been demonstrated, sometimes productised. The system level design of the mission is, however, much more complex, requiring the solution to many of the problems of hugely parallel, self-organising, ad-hoc systems which form the core of the research agenda for pervasive computing.

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