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ON THE ORIGIN OF SATELLITE SWARMS

C.J.M. Verhoeven[1] , M.J. Bentum[2,3], [,4], G.L.E.Monna, J.Rotteveel[5]
(c.j.m.verhoeven@tudelft.nl, m.j.bentum@utwente.nl, b.monna@systematic.nl,
J.Rotteveel@isispace.nl)

[1]Technical University of Delft, Faculty of Aerospace Engineering - Space System Engineering,
Kluyverweg 1, 2629 HS Delft, The Netherlands

[2]University of Twente, Faculty of Electrical Engineering, Mathematics & Computer Science,
P.O. Box 217, 7500 AE Enschede, The Netherlands

[3]ASTRON, P.O. Box 2, 7900 AA Dwingeloo, The Netherlands

[4]SystematIC Design, Motorenweg 5G, 2623 CR Delft, The Netherlands

[5]ISIS - Innovative Solutions in Space, Rotterdamseweg 380, 2629 HG Delft, The Netherlands

For a species to develop in nature basically two things are needed: an enabling technology and a “niche”. In spacecraft design the story is the same. Both a suitable technology and a niche application need to be there before a new generation of spacecraft can be developed. In the last century two technologies have emerged which had and still have a huge impact on the development of technical systems: Micro-Electronics (ME) and Micro-Systems Technology (MST). Many different terrestrial systems have changed dramatically since the introduction of ME and MST and many new systems have emerged. In the same period many nano-satellites have been built and launched and shown that they can perform in space. Still it is not clear what the specific role of these small satellites will be. Where will they go? What will they do?

1. INTRODUCTION

Both Micro-Electronics (ME) and Micro-Systems Technology (MST) are ruled by Moore’s Law that indicates that considerable technology updates appear at the pace of years or even months instead of decades. Systems that need a development time of more than a few years will inevitably be based on “out-dated” and thereby difficult to maintain and repair technology unless during the development constant redesigns are made. This makes the development of these systems at least very expensive.

Although expenses do not seem to be a frequent show stopper in the design of a spacecraft, it is still very interesting to investigate what system architectures might evolve when the specific properties of the new technologies ME and MST are fully exploited.

ME presently offers more than 2 billion transistors on a chip and MST offers mechanical systems like resonators, mechanical switches, propulsions units, gyroscopes and many other sensors that fit in a volume of a few square millimeters to a few centimeters. So it is possible to fit a lot of signal processing power together with the necessary sensors and actuators in a volume that is really very small compared to any know space system.

Of course state-of-the art spacecraft will immediately outperform these units in all aspects apart perhaps from cost and quantity. But for the first time it seems to make sense to envisage the operation of formations of tens to hundreds of satellites that are cheap because they are based on standard commercial COTS technology and system designs. These satellite swarms will not be the systems that replace all other space systems. But, like in nature, there must be a niche where swarms are the optimal solution.

It’s time to start finding the niche and occupy it.

2. Swarms

Typical properties of a swarm in nature are robustness, redundancy, large area coverage, the lack of a hierarchical command structure, limited processing power per unit and self-organization (“swarm-intelligence”).

It is important to review each of these properties carefully when thinking about the design and implementation of a satellite swarm. Obviously swarms will not be suitable or optimal for many tasks but there are some that can only performed via a swarm.

3. Robustness and redundancy

Swarms are not necessarily robust because their units are robust. The robustness of the swarm follows from the fact that none of the elements in the swarm is essential for the functionality. Of course every unit needs to be designed robust enough to have a good chance to survive but it is not necessary to go to extreme redundancy techniques. It is not necessary to have a single-point-failure free design. When all units are physically identical it may still be possible for a unit to specialize by reconfiguring itself but this reconfiguration option then exists for every unit so the robustness of the swarm is not affected. Reconfiguration is technically seen not too complicated for a modern Micro-electronics system. From the functional point of view there is the danger that the decision to reconfigure of a unit leads to loss of the unit for the swarm. And when the incentive to reconfigure is common for all members of the swarm, disaster strikes. In nature the units of a swarm do not seem to have much learning power. Perhaps the ability to learn is a lethal property in the end.

This thought led to a new insight in the engineering team in Delft working on nano-satellites. Physically it is easy to fit a strong processor in a nano-satellite. It becomes problematic to really make it perform. Small solar panels will not be able to support the power needs of the processor and modern high-performance processors tend to get very hot. It will be very difficult to keep the nano-satellite cool enough. This trend of processors getting better and hotter and satellites getting smaller looked like a real problem. Swarms in nature show that the processing power in a unit can be very modest. The intelligence is in the swarm and not in the separate units. This does by no means make the design problem easier but is shows where the effort should be. Not in trying to squeeze as much processing power as possible in one unit and solve the overheating problem, but in trying to find the correct primitive behavior of a unit such that when it interacts with other units sufficiently intelligent behavior of the swarm is obtained. And even the demand on this intelligence should be modest. A swarm can perform simple tasks, like finding one specific sort of measurement data (finding food), in a very reliable way. To perform another task, another swarm should be built. When the units are cheap enough, this could still be much more cost-effective than the design of a single more intelligent swarm.

For robustness, the focus is not on processing power but on large numbers and (modest) intelligence on the swarm level.

The large numbers give a redundancy level that is not attainable in a single satellite. Also the fact that the volume in which the swarm is, is much larger than the largest satellite there is a much larger chance that the swarm survives when it is hit by space debris.

Still a lot of research is necessary on the behavior of a swarm with respect to unforeseen situations. Larger satellites can usually be controlled via a ground station so in an unforeseen situation it s possible to keep the satellite from maneuvering itself into a disastrous situation. For a swarm it may prove to be much more difficult to do this.

E.g. it is well known that it is easy to catch wasps using a bottle that is closed at the top and has a hole in the bottom. Some sweets in there lure the wasps inside. Although the bottle is open at the bottom, their reflex of flying upward towards the light to escape keeps them in the bottle where they die eventually. If a plant emerges that has a fruit with the properties of this bottle, wasps will become extinct. It is important to find methods to prevent these lethal reflexes in a satellite swarm

4. Where do they go?

There is no good reason to bring a swarm into orbits that are occupied by normal satellites right now. Conventional scientific instruments will, at least at this moment, outperform instruments that fit on a nano satellite. This means that there is no market for the measurement results of the swarms which will form a huge financial obstacle for the development of nano satellite swarms. During the whole research phase the swarms will economically seen just add to the large amount of space debris that is already there. Apparently there is no “niche” around the earth where swarms can grow towards maturity. If satellite swarms will ever mature, it will not be in the standard earth orbits. It is more likely that swarms will go to places that are difficult or impossible to reach or too dangerous for standard spacecraft [6]. The most likely place for a first swarm to go to is probably the moon. For further travel the TRL of the nano satellites is still too low. The moon can be reached.

There are three really different ways of bringing a nano-satellite to the moon ad hopefully in a moon orbit that could technically work. They are:

1. Launch via a dedicated launcher
2. A piggy-back launch via another moon mission
3. A piggy-back launch to an earth orbit of satellites that can fly to the moon themselves

Option 1 would only be realistic for organizations like NASA or ESA and seems financially unfeasible at the moment. Option 2 is still an expensive option and there are not many opportunities. It is also questionable if the main payload of such a mission likes the idea of bringing its own "space debris".
Option 3, seems the most feasible for a swarm. The feasibility of a piggy-back launch has been demonstrated already many times. There is a lot of research going on in the field of micro propulsion systems that can fit in a nano-satellite. The feasibility of a typical micro-propulsion system will be shown in the coming launch of Delfi-n3Xt, a new Dutch nano-sat to succeed the very successful Delfi-C3 [1,2,4]. (Electric) micro-propulsion systems are able to deliver a small thrust for a very long time. In a matter of months they can bring a nano-satellite to the moon or beyond. Though the third option needs much more research and development time it has the most similarity to swarms in nature where the units are also able to move around by themselves.
It seems to be the most realistic to identify the first potential niche around the moon where the units of the swarm go by themselves.

5. What will they do?

Typical features of a swarm, apart from robustness and the potential to go far away are the large area it can cover and the availability of many modest processing units. Many sensors can be spread over a large area giving good spatial resolution. The simplest sensor that can be imagined is an antenna and it is reasonable to imagine that the first scientific measurements a swarm could do would be measurements of radio signals. Radio astronomy could be a very interesting research application for a satellite swarm [5]. There are enough examples of antenna arrays for radio astronomy that artificially increase the aperture by using multiple antennas [3]. Shielded by the moon from the disturbances of the earth an orbiting antenna array could do measurements that cannot be done in another way. Especially at very low frequencies, below 30MHz measurements by a swarm around the moon could add new science. This would certainly be a niche application in which it is worth to spend money on a satellite technology with a low TRL, low performance that is mainly built with the normal, cheap but very modern COTS technology. This could be the niche where nano satellites and swarms can become mature. And for the matured systems many other applications that are beyond feasibility right now will open up.
The Dutch OLFAR project (Orbiting Low Frequency Array) is an example of a moon orbiting radio telescope based on the swarm principle. Details on this radio telescope are discussed in another paper on this conference.

6. Power

Small satellites always have power problems. To keep everything within practical limits for launch, solar panels cannot be very large. Also it is questionable if an attitude control system that can keep solar panels pointed towards to the sun remains feasible when the satellites shrink. (Attitude determination of a spinning satellite may be sufficient for the scientific mission.) Missions beyond the moon will certainly create a delicate power situation when the mission is not in the direction of the sun. A simple solution to this problem is well kown for common laptops,, and is also used in the Rosetta spacecraft: hibernation. Rosetta relies solely on solar panels to scavenge energy and reduces fuel and power consumption by switching off nearly all equipment when no scientific activity is needed. There are many ways to scavenge energy during a mission. Though most of the time the amount of scavenged energy does not suffice to enable constant full operation of a single satellite, the total amount of scavenged energy in a swarm may be enough for constant operation of the swarm with a sufficient number of active satellites. This is only possible when the number of satellites is high enough.

Since there is no coordination in a natural swarm (i.e. the units are not aware that they are part of a swarm) power scheduling will be difficult to coordinate on the swarm level. But simple scenarios can be imagined. It could be a reflex of a satellite to hibernate when it receives too may signal power of other satellites in the swarm. The swarm would always maintain a certain radio power level that is lower than the power that could be generated if all satellites would be active. That higher level could not be maintained, but the reduced level can be maintained permanently if the number of satellites is high enough to give hibernated satellites enough time to recover. If this is not enough and the level drops below a certain level all satellites could decide to hibernate for a predetermined time (winter sleep).

An interesting aspect of this is that the number of units can be increased gradually over the years, either giving the swarm more uptime (less winter sleep) or more active satellites.

Power will not be a fundamental problem in a swarm. A power problem can always be solved by using more satellites.

Also for transmission power used by the radios to relay gathered information back to earth there is a “swarm way” to do this. As stated before, the satellites are not aware of the fact that they are in a swarm. But receiving a radio transmission from another satellite may stimulate a satellite to start to transmit too in a coherent way. Without further coordination the result would be a transmission power level that increases with the number of available satellites. Insects tend to generate coherent scent pulses in a similar way. Of course there is the problem to direct a beam towards the earth. Help from the ground station in the form of a beacon providing feedback might help. It will be less of a problem for the ground station to generate a feedback beacon with enough power.

Processing power is clearly a matter of having enough satellites and enough time. A swarm might be able to switch between two modes. A capturing mode and a processing mode, like finding food and digesting it. Coordination can perhaps take place in a similar way as described above for the other two power cases. Still a lot of (very interesting) research needs to be done to see something really sensible about this. What is clear is that increasing the number of satellites will help.

It can be concluded that still large challenges exist with respect to power in a swarm, but also that increasing the number of satellites always makes life easier. Nature shows that this “large number advantage” resulted in extremely durable and efficient species; exactly the kind of species that would be able to survive in a harsh environment like space.

7. **CONCLUSIONS**

In this paper some ideas were presented about the role of nano-satellites and swarms of these satellites in space research. At first sight the swarm idea is very attractive but still an incredible amount of research needs to be done before the swarm concept can be tested in practice. A major problem is finding the funds to start the research. Although some state that swarms can be excellent performers exploiting the best of modern technology there seems to be no market for the data that could be obtained with swarms at the present level of development. These swarms would be outperformed on all aspects by standard spacecraft. It looks like swarms are not needed for the usual tasks. Is there no commercial niche? Swarms of cheap small satellites would be able to sustain a constant flow of low quality data, like tracking or tracing of objects on earth. (e.g. ships) . Swarms might prove to give a good quality to cost ratio there. It could very well be their niche application in earth orbit.

Purely scientific niches certainly do exist. The most realistic example of this is the OLFAR project, building a swarm based radio telescope around the moon. There is no other way to obtain the data that OLFAR can obtain. New science has always been a reason to fund high risk projects. Mostly these projects resulted in increased maturity of the technology in such a way that it becomes commercially interesting. It is also very likely that projects like OLFAR result in matured nano-satellite and swarm technology for space. And at that moment nano satellites and swarms of them will be able to compete with standard space craft and, if the numbers are large enough, outperform them.

It looks like satellite swarms are going to follow the traditional evolutionary way of technical development. They start in an exotic purely scientific niche, become mature, raise commercial interest, lead to new products and services, outperform older systems and take their place in common space craft design thereby giving the opportunity for new and very different players in the space market.

8. REFERENCES

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