Bacteria, polyps, ants, and bees are the living proof that, given inhospitable conditions, colonies stand a better chance of survival than individuals. At TU Delft, this biological principle is now being used on spacecraft. A colony of micro satellites will be less vulnerable than a «normal» satellite, not only to gamma radiation and solar storms, but also to cutbacks. After all, micro satellites are small and light, and will — someday — be mass-produced.

Nature is a source of inspiration not only to artists, but also to engineers. At least, it is to Dr. Ir. Chris Verhoeven of the department of Microelectronics at the Information Technology and Systems (ITS) faculty.

‘Name the one most successful type of organism on Earth,’ he says. Count out elephants, whales, or any other of the large mammals. All of these are facing extinction because their habitats are rapidly being wiped out or polluted. The most successful animals on our planet are those that live in colonies, ants for example. Their combined biomass far exceeds that of elephants and whales, and what’s more, they can be found all over the world. The success of ants living in colonies forms the source of inspiration for what Verhoeven calls his boyhood ambition, which is to have colonies of micro satellites that can be used both for earth-based tasks (such as telecommunications and earth observation) and for exploring the solar system and beyond. Instead of having a single Starship Enterprise, which is far too vulnerable, we would have dozens of small spacecraft the size of a shoe box.
University satellites

Even space travel cannot escape the truism that the longest voyage starts with a single step. That first step is to actually develop a micro satellite that is small, light, and cheap enough to be manufactured and launched in relatively large numbers. The current generation of micro satellites, a number of which have been developed and built by universities, is still too heavy and too expensive.

‘What we need is a quantum leap,’ says Dr. Ir. Wim Jongkind of the department of System Integration at the faculty of Aerospace Engineering, ‘a fundamental reshaping of systems and in particular, the connections between the systems on board satellites.’

Jongkind, who has been closely involved with Dutch space engineering activities since 1964, is the coordinator of the micro satellite project, or MISAT. In fact, it is a cluster of projects that form part of MicroNed, a micro systems technology research and development programme (see text box). To find funding for the MicroNed programme, the Dutch BSIK knowledge infrastructure investment programme (a 900 million euro nest egg based on natural gas profits) was tapped into.

Although the current generation of university-developed micro satellites is characterised by its relatively low cost, according to Jongkind they also suffer from less than optimal design, low precision (positional and orbital), and high risk of failure because the systems are not fully redundant, in other words there are insufficient backup systems. As a result, the failure of a single component jeopardizes the entire satellite. What the proposed Dutch micro satellites have in common with the current generation is that they are small and light, but they differ in that they feature high orbital accuracy, accurate position control, low energy consumption, and a high level of redundancy. In addition, satellites should be adaptive thus capable of adapting to changing conditions.

Blue Tooth

To meet these apparently conflicting requirements, the project requires the support of micro technology and advanced ICT techniques. Jongkind: ‘One of the reasons why satellites are relatively heavy is that the wiring between the various parts does not lend itself to miniaturisation. Therefore a different solution must be found. One option is to combine several components as microstructures on a single microchip. DIMES, the institute for microelectronics and submicron technology of Delft University, has a lot of know-how in this field. As an option for wireless connections, Blue Tooth or infrared communication was suggested, the type of communication technology that by now is part of the standard package offered by any cell phone. But at the moment Delft scientists have opted for ultra-wide band communication. What’s more, interconnection of satellite parts could be simplified by adopting a single plug-and-play standard, say USB-like protocol. This fits in well with the aim of the European Space Agency which is to stimulate recycling and series production of parts to minimise mission costs.’

Wine glass gyroscope

Proposals are put forward for the development of different micro systems as part of the micro satellite research programme. One example of this is the development of a micro navigation system in which the instruments for controlling attitude and orbit are combined in a single microchip that includes the ancillary electronics. This type of chip would have to contain a gyroscope, an accelerometer, and a magnetic sensor to control the satellite’s attitude relative to the magnetic field of the earth or another planet or star. Miniature versions of each of these different components are already available. For example, a U.S. company currently produces a ‘wine glass’ gyroscope measuring 10 x 10 millimetres, and a miniature version of the magnetic sensor based on single electron tunnelling (SET) technology also exists. Lastly, the accelerometer is a well-known component found in car air bags. The trick is to combine all these different components in a single microchip and eventually find a way of producing them reliably in series.

Other research proposals relate to the development of miniature versions of other components of AOCS, the Attitude and Orbital Control System. These include optical systems that use the sun (a miniature sextant) and an accelerometer based on a spring-loaded mass system.

Another major issue is that of cooling. In our solar system at least, exterior temperatures can vary considerably, so an active control system is required to keep the temperature of the satellite within acceptable limits. Moreover, micro systems generate heat which has to be extracted. Since space is a vacuum, air cooling (or convective cooling) is not an option, so the heat from systems and –
insofar as still present – wiring and ports must be removed by means of conduction and radiation. The Infrared Astronomical Satellite (IRAS, launched in 1983) enabled the Netherlands to gain quite a bit of expertise in the field of cryogenic liquid cooling systems. In IRAS, the infrared detectors had to be cooled with liquid helium to 2 degrees above absolute zero. One of the research proposals is aimed at utilising this know-how for the development of miniature cooling systems.

Wireless transceivers The avenue being explored for the communication between satellites and ground stations and for inter-satellite communications is a wireless receiver/transmitter that adapts to different conditions and tasks. In other words, a system that is continuously being reconfigured. Depending on the conditions, the electronics could autonomously configure a receiver/transmitter for short-wave use, for instance for a communication link to Earth, or into a giga hertz-range transceiver. All it would take would be to feed different commands to the same components, or change the connections between them. Verhoeven is the project leader for this part. ‘Wireless transmitters are still being constructed according to principles laid down in the nineteen thirties when vacuum tubes ruled the roost. The design of a transceiver takes into account the receiving conditions. The designer will assume the worst possible conditions, so he will be designing a transceiver suitable for conditions that rarely, if ever, occur. This results in excessive power consumption, and still conditions may present themselves with which the transceiver will not be able to cope,’ Verhoeven says. These days, vacuum tubes have been replaced by transistors, with microchips packing hundreds of thousands of them in the space of a few square millimetres.

Verhoeven: ‘We have much more processing power at our disposal which we can use to design a transceiver that will adapt to current conditions. We can thus greatly reduce power consumption while the added advantage is that the colony can autonomously adapt the means of communication to new tasks as the expedition progresses.’

Memory metal Most earth-based systems do not readily lend themselves to use in the harsh conditions in outer space where they are constantly being bombarded by space debris, X-rays, neutron and gamma radiation, as well as the occasional solar storm caused by eruptions of hot plasma. To minimise damage from meteorite impact, a research proposal has been drafted to develop a smart memory metal or SMA (smart metal alloy), in particular using aluminium capable of restoring its former shape. Prof. Dr. Ir. Sybrand van der Zwaag of the faculty of Aerospace Engineering has conceived a self-repairing system consisting of an aluminium grid containing granules of memory material. A thermal treatment is applied to push the granules just beyond their state of equilibrium, so they remain on the brink of their energetically optimum state.

Van der Zwaag: ‘Suppose a satellite is hit by a piece of space grit, creating a small crack. This crack will tend to grow, but it is stopped in its tracks by a granule of memory metal which absorbs the energy from the crack and uses it to regain its energetically optimum state, thus limiting the impact damage. Even better, the damage could be repaired by exposing the metal to a slight rise in temperature that would push the granules back beyond their state of equilibrium. In other words, you could repair the damage in flight, which would enormously extend the life cycle of the micro satellite.’

Super telescope Since micro satellites are small and cheap, they can be produced in large numbers. We can thus shape the colonies so as to reduce their vulnerability and improve their reliability. A first step in this direction is the European Space Agency’s Darwin project. This consists of an array of six infrared telescopes positioned so as to form a system that can be configured for use as a single giant telescope, like the Synthesis Radio Telescope at Westerbork, where fourteen 25-metre diameter telescopes together form a super telescope with an aperture of one mile.

For Verhoeven, the Darwin project is still too static with satellites that are too big and vulnerable. His concept involves a swarm of dozens of identical micro satellites, each of which on its own would be of little use, but which acting together as a colony would have the necessary intelligence for example to investigate a comet and possibly even land on its surface. Like an ant, each single satellite would have the capacity to execute all of the tasks required, but

MicroNed lays foundation for microsystems

MicroNed is a consortium of eight universities and research institutes and 22 industrial partners. The consortium has submitted a plan to the government to reinforce the micro systems technology infrastructure. The government has decided to grant 28 million euro for distribution to MicroNed, including Microsat. The question put to the project leader, Dr. Ir. Fred van Keulen, professor at the Faculty of Design, Construction and Production, is why micro systems should require government funding. Why should normal market mechanisms not be up to the job?

Van Keulen: ‘The problem is that the activities in the field of micro systems technology in the Netherlands tend to be rather fragmented. One could consider leaving it to the market to find a way of undoing this fragmentation, but then you would miss the boat. It is the very nature of micro systems technology that forces us to structure and stimulate collaboration between the various disciplines and between research institutes and the industry. For example, there are scale effects to take into account; a liquid acts very differently inside a channel a few micrometres in diameter on a chip than it would inside a pipeline half a metre wide. The production process also affects the properties of the product. Therefore, the development of micro systems forces us to transcend the boundaries between the disciplines.’

A) This German mini satellite (which has had some of its solar panel cladding removed) is a study object at the faculty of Aerospace Engineering. Its twin is currently circling the earth. The satellite is still rather big due to the «classic» way the electronics of the device have been constructed. Making full use of the possibilities offered by microelectronics and micro-systems technology will enable us to reduce its size further. The wiring and galvanic insulation between the various components still take up a great deal of the volume and weight of the satellite and are the result of stringent requirements regarding the satellite’s reliability. In the MISAT project, the focus is on the reliability of the colony as a whole, which is why the requirements for the reliability of individual satellites can be more relaxed. Moreover wireless communication between the various components of the satellite is being considered in the same way. Blue Tooth is being used to link computers, printers, and networking systems in the wireless office.

B) Wiring detail. Since the satellite will be operating in what is practically a vacuum, the use of standard wiring or connectors is out of the question. Gases trapped inside the insulation of a wire could suddenly escape, destroying the insulation. Certain metals used in standard connectors on earth would quickly evaporate in space. The quality of a connection in an earth-bound connector would rapidly deteriorate in space. This makes wiring a satellite an expensive exercise as well.

C) The exterior of the satellite is covered in solar panels. A central power supply system distributes the power from the solar panels among the various components of the satellite, including the batteries, which provide the satellite with power while it is in the earth’s shadow. In the MISAT project, certain components may get their power from their own solar panels, with local battery support if necessary. This would limit power supply problems to certain components without affecting the operation of other parts of the satellite. An autonomous sensor system can also establish contact with another satellite from the colony if part of its system fails, thus ensuring that the information provided by the still functional sensor in the partially disabled satellite would not be lost to the colony.
by creating a division of labour, the colony will be able to function as a super organism. ‘Suppose you have forty micro satellites,’ Verhoeven says. ‘En route to the target comet, one quarter of these will fail, but the remaining satellites together still form a fully functional system. If ten of those were to land on the comet’s surface, in the process of which half would be destroyed, you would still have a fully functional system in place. If during the attempt to land on the comet’s surface all, or almost all, of the satellites were to be destroyed, the system would have to be intelligent enough to decide to abort the attempt.’

Portuguese man-of-war It sounds like science fiction, a swarm of micro satellites that – on behalf of humanity – explores the solar system and beyond. But according to Verhoeven, nature itself shows that relatively unintelligent creatures together demonstrate a certain measure of intelligence using simple rules for intercommunication. If you look at a single ant, its behaviour appears to be rather disorganised and relatively simple, but when you observe the behaviour of the colony as a whole, it is remarkably consistent.

‘This phenomenon is not limited to ants and bees, Verhoeven explains, ‘it also occurs in lower organisms, such as certain types of jellyfish. The Portuguese man-of-war for example, one of the deadliest species of jellyfish around, appears to be a single animal, but is in fact a colony of collaborating polyps.’ Even our own brain could be considered a colony of collaborating neurons, according to Verhoeven. ‘We have manufactured components with single-electron tunnelling transistors whose behaviour is comparable to that of neurons. The small networks we are currently capable of constructing are still limited in use, but I think that it won’t be long before we can imitate the neural network of say, a worm. Once that can be done, building an ant is a small step. The real challenge will be to find out what the mechanisms, rules, and algorithms are that make a colony more intelligent than its constituent parts, the individual animals, and to use that knowledge to create an artificial colony capable of surviving the extreme conditions of outer space.’

Climate research The Dutch micro satellites offer opportunities for research into the rules of behaviour that impart intelligent behaviour to a colony, for example by launching two micro satellites that will collaborate with ten or twenty virtual satellites on a computer. In the meantime, the two micro satellites can also be used to perform other tasks such as high-accuracy measurements of the earth’s field of gravity, or measuring the density in the upper layers of the atmosphere. The latter is important for long-term weather forecasts, but is still little done because satellites at that altitude suffer greatly from the effects of solar storms. Another possible application will be to measure the composition of the atmosphere at an altitude of several hundreds of kilometres, data that are crucial to climate research. These applications alone would justify the development of a new generation of micro satellites. The research into colonies of micro satellites would simply be a bonus. Added to this comes the fact that the development of micro components may produce an even bigger spin–off in the form of new and improved earth-bound products than traditional space exploration has done. ‘Moreover,’ Jongkind says, ‘Dutch research and industry will be greatly stimulated if the Netherlands manages to be the first to develop a new generation of micro satellites. To me it appears to be the next logical step, after the traditional carrier to which the other units are connected, coordinates the behaviour of the satellite, handles communications with the outside world, and maintains wireless links with the payloads (sensors and experiments). If the bus system fails, the payloads can contact the bus system of one of the other satellites. In future, building a micro satellite will involve little more than bringing together a number of units. Few, if any, physical connections will be required. This makes it possible to vary the composition of the satellites at minimal cost. Reliability can be improved by using units that have proved their worth during earlier flights. The plug-and-play concept will substantially reduce the cost of space exploration.’

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In a colony of satellites the various tasks can be efficiently distributed. Although each satellite by itself can contact the ground station, the task can be left to a single satellite allowing the others to save energy by limiting communications to exchanges within the colony. If the satellite maintaining the link with earth should fail, or pause to recharge its batteries, a different satellite can take over. Their collaboration within a colony enables the satellites to form a giant virtual antenna that could maintain contact with the earth in spite of adverse conditions. They could also act as a single giant radio telescope. The Darwin satellite system is an example of this technique.
The electronics inside the micro satellite will have to be highly flexible. This micro chip designed at Delft is part of an early experimental radio system that will be fully reconfigurable during flight. The wireless chip will have to be able to handle all communications, both internally and with the rest of the colony and earth. Finding the optimum configuration will ensure that power consumption can be minimized.

Oscillators are important components of any communication system. This detail shows a quadrature oscillator consisting of two coupled relaxation oscillators. This patented circuit was developed at TU Delft and will form an essential component of the reconfigurable transceivers.
Communication with satellites requires a perfectly operating ground station. To get off to a good start, work on a new ground station has already begun on the 22nd floor of the faculty of Electrical Engineering, Applied Mathematics, and Information Technology. The ground station’s array of aerials will consist of two Yagis and a dish aerial. The number of satellites currently in orbit is sufficient for practice purposes. On 8 August 2003 an improvised set-up was used to establish the first contact using the OSCAR 40 satellite with a radio ham in Pennsylvania. The ground station that day consisted of an Icom transceiver and a Yagi aerial (which for lack of a rotor device had been strapped to an office swivel chair). The satellite was tracked by carefully swivelling the chair. The aerial platform can be viewed through a webcam at http://delficam.ewi.tudelft.nl