Title: Swarming satbots
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Abstract:

Creating microsatellite robots (satbots), which can survive individually and connect with others as a working group, can deeply impact space studies. Given the way all space related equipment has bloated in size, it seems important to reevaluate simple designing. The satbots should be able to survive in space. The technology and implications are also discussed.

Full Text:

A radical new approach to designing satellites aims to create microsatellite robots (satbots) that survive individually in the space environment and can be harnessed collectively to do specific tasks.

When the Galaxy 4 satellite began rotating uncontrollably in May, millions of pager users lost their paging service, National Public Radio listeners couldn't listen to All Things Considered, and electronic data service users couldn't retrieve the news and information they needed. The satellite is still in a stable orbit, but it has lost its ability to point at Earth.

Pointing a satellite in the right direction is fundamental to its mission. To stay "alive" it has to point toward the Sun; to talk to Earth and to other satellites, it has to point toward them. The technology for pointing the satellites, called the attitude control system, is traditionally a quite sophisticated combination of sensors, actuators (which move the satellite), and control logic (usually a computer that converts the sensors' data into commands for the actuators).

We believe it should be relatively easy, based on new design approaches, to build control systems that keep spacecraft alive by pointing the solar panels at the Sun, keep satellite instruments pointed at Earth, and keep communications hardware pointed at neighboring spacecraft. All autonomously.

What can go wrong?

The U.S. Department of Energy launched the small satellite Alexis in 1993. It weighted 525 kilograms, took several years to build, and cost $17 million. Alexis' primary mission is to test new X-ray imaging technology that could be used for both astrophysics and nuclear weapons test verification. To fulfill these missions, Alexis must be able to point in a precise direction. Hence, it uses a modern spacecraft attitude control system to orient itself (see sidebar).

The control computer relies on measurements of the magnetic field at the magnetic field at the spacecraft that were provided by a sophisticated magnetic field sensing instrument called a magnetometer. However, by the time Alexis was in space, the magnetometer had failed. As a result, the control computer couldn't figure out how to control the actuators. Fortunately, the Alexis personnel, through incredible perseverance and cleverness, were able to save the mission by replacing the onboard magnetometer-based attitude control with commands from the ground.

Alexis ended happily. However, other satellites have had control system failures and have not been as lucky. How can these failures happen after so many years of outstanding space engineering? If failure rates cannot be eliminated, can they be reduced? And how can we minimize the losses when they do occur?

Why do satellite control systems fail?

Sputnik, the very first spacecraft, was about the size of a basketball and simply beeped. The space race between Russia and the United States was on, and the first round was won by a small spacecraft that could be put together quickly and survive.

A spacecraft that performed work would have been more complicated, would have taken longer to build, would have cost more, might not have worked, and would have lost the race. In such a race, simpler is better. Suggesting something as difficult and complex as the Hubble telescope would have been crazy.

As space technology advanced, launch vehicles became more powerful and more costly, so it was natural and imperative that each spacecraft launched do as many different things as possible. Hence spacecraft have grown to be large and complex machines, such as the Hubble telescope, which is roughly the size of a schoolbus and performs multiple sophisticated functions.

Getting machines to work in space, however, is tricky.

First, spacecraft are like robots. They either are autonomous, controlling themselves, or are remotely controlled. If they stick or get confused, we cannot give them a nudge. If the master computer glitches, we cannot hit the reset button.

Second, space is a harsh environment. Not only must spacecraft withstand incredible accelerations during launch but they also must function flawlessly in the searing heat, bitter cold, radiation, and hard vacuum conditions of space for 3 to 10 years, the life of the mission. Furthermore, they can be hit by dust particles and meteors traveling at many miles per second.

The way we typically design robots and satellites to survive in harsh environments is first to characterize the environment and then to devise engineering solutions that work in that environment. A key concept has been subsystem engineering: breaking down the complex system into smaller subsystems--which can each be designed, built, and tested to meet certain specifications--and then very systematically assembling the subsystems. In principle, if only so many things can go wrong in space, then it should be possible to determine all the possible failures and provide fixes, such as radiation shielding and backup components, for them.

So the space field has marched forward from silly little beeping basketballs to ever bigger and more complicated spacecraft, with each successive spacecraft doing more and/or better work than the previous one.

Unfortunately, despite the best efforts to design for all possibilities, spacecraft are still prone to catastrophic failure with no alternatives. In fact, the faster and more complicated and powerful that computers have become, the more they have been prone to mission anomalies.

Mimicking animals' metronomes

Since failures appear to be inevitable and may even be aggravated by modern computer solutions, we are reexamining the engineering methodology. Early spacecraft were small, simple, and survival-oriented. Maybe we should investigate a survive first, work second engineering paradigm. Maybe subsystem engineering is not the best way.

Animals appear to have neurons that make metronomes called central pattern generators (CPGs) that control walking, the heartbeat; and many other autonomous functions. In the last few decades it has been demonstrated that very simple electromechanical systems based on CPGs can often exhibit remarkably complex behavior. Psychologist Valentino Braitenberg's research implied that some "conscious" behavior may simply be "in the wiring." Rodney Brooks of MIT has pioneered the hardware realization of these ideas by applying his own concepts of subsumptive architectures (cooperative hierarchical structures) to create very capable robots.

One of the authors, Mark Tilden, has constructed electronic CPGs with a minimal number of components and used them as the foundation for building robots that are simple, low-power, and cheap. Tilden's robots are also tightly coupled to the environment, extremely capable and robust, and appear to demonstrate emergent collective behavior. We decided to investigate this technology for satellite attitude control systems.

We built a two-neuron CPG for the control logic of our satellite controller. Although both the neurons and the resulting CPG are extremely simple, we believe they are radically important as the building blocks upon which it may be possible to construct a whole menagerie of useful space tools.

Conventional controllers calculate control signals for actuators based on data from sensors and possibly additional information from the ground. In contrast, our controller, the simple CPG, is directly driven by the environment. Calculations are done in analog (see sidebar). We don't need separate electronics and computers to process the sensor information. We don't need commands from the ground to operate. Our system is simple, low-power, fault-tolerant, and autonomous, This all means big cost savings without big sacrifices in performance.

This CPG could easily be used as a backup controller for the present digital versions. It is so small, lightweight, and low-power that it would be virtually unobtrusive to existing spacecraft. It could use the same coarse Sun sensors and the same actuators that already exist on spacecraft. It could control not only magnetic torque actuators but essentially any active actuator system. And it could work autonomously to keep the spacecraft alive in case the main control system fails.

However, we realized that it may be possible to go further. First, our controller can use other sensors besides the Sun sensors. We could use radio or laser sensors to point at other satellites that transmit information over laser or radio links. This is important for space communications. We can use multiple sensors to control the CPG, and we can use multiple CPGs to make more sophisticated systems. This is the foundation upon which we assert that it should be relatively easy to build control systems that, for example, keep spacecraft alive by pointing the solar panels at the Sun, keep satellite instruments pointed at Earth, and keep the communications hardware pointed at neighboring spacecraft. All autonomously.

We also realized we might be able to shrink spacecraft significantly using these biologically inspired techniques. It may be possible to seriously contemplate flying lots of microsatellite robots (satbots) to do missions not previously possible. So far, we have shrunk the controller so that its power requirements, size, and communications needs are not the limiting factors as we try to shrink the complete satellite. To make smaller spacecraft, we also need to shrink the actuators, sensors, power systems, and communications hardware. Fortunately, many other bright people are working creatively on these things and making progress. Our approach offers great promise for shrinking these subsystems and linking them together.

Where are we headed?

We have only begun this research. It may not prove useful, but we intend to find out. The following are some preliminary ideas for future research. They are not necessarily new or original, but we may for the first time be able to realize these dreams.

Flying lots of tiny satellites may be exciting to some people, but the existing and irreplaceable big spacecraft community sees this as adding more junk to an already huge pile of space debris. Our satbots need to be able to avoid hitting big spacecraft. It also might be useful to have them attracted to big hunks of space junk to remove space debris. This means they have to "see." We are working with Derek Abbott and his collaborators with CHIPTEK in Australia. Abbott's group has developed a collision detection and avoidance system for cars based on insect vision chips that mimic the way bees navigate. They are investigating the use of their chips, or some modification of them, for satellite collision detection.

Radioactive thermal generators have proven useful for deep space missions, where there is not enough sunlight to use solar cells. However, since these missions have used technologies that needed a lot of power, they have used a pretty good chunk of radioactive material. Now people are concerned about that much radioactive material being dumped back down on them if the launches have failures. Our circuitry is so low-power that it would not be necessary to fly very much radioactive material at all, making this technology useful again.

The spacecraft structure is really only needed for launch. Once in the weightlessness of space, the required structural strength is much less. As several other people have suggested, it might be possible to make the structure the battery by using technology like polymer batteries. It might also be possible to have the spacecraft effectively "eat itself' by consuming the launch structure for energy.

Sensors are becoming smaller and smaller. Our prototype satbot, using a magnetic torque actuator and photodiodes, automatically changes its behavior when the magnetic field in space changes. Therefore, it is in effect a magnetic sensor. This raises the intriguing possibility of replacing the entire sophisticated machinery of a conventional magnetometer with a satbot. Other researchers at Los Alamos are investigating the use of photodiodes for measuring space plasmas. If their work proves successful, then it may be possible to use the same photodiodes to both seek the Sun and measure the ambient space plasma.

The way we currently forecast space weather with a few big satellites is like predicting global weather with just a couple of really precise weather stations. If we can build simple and cheap satbots to measure magnetic fields and plasmas, we could enter a new era of space weather forecasting more similar to the way we forecast weather here--with lots of less-precise weather stations spread all over the world.

As we mentioned before, it may be possible to have our satellites point automatically at other satellites, enabling lower-cost radio and optical communication networks in space. The implications are far reaching.

One exciting area of research is cooperative behavior. Collective behavior can be a powerful technology. Just look at ants, or even humans when we can get along with each other. Fireflies can synchronize their flashing, enabling them to be seen for miles when the individuals cannot. Tilden has observed collective walking behavior in his robots. Could swarms of satbots synchronize like fireflies to beam back a message that no individual satbot could? Could they swarm around space debris and remove it as an immune system does? We are investigating these areas.

Finally, our approach may eventually produce systems with emergent properties such as self; assembly that have not been possible to achieve with conventional approaches. Our neurons interact with sensors and actuators in a simple and direct fashion--through wires and resistances, not through complicated connectors, predefined cabling, or software. Therefore, our neurons can receive inputs from multiple sensors of different types, and the neurons' outputs can go to any electronically controlled actuators. With this type of interconnectedness, the whole system should be able to respond in a natural and acceptable manner. This flexibility, coupled with the flexibility to connect neurons in a rich variety of ways, makes dreaming of self-assembly possible.

Can satbots with different capabilities join in space and become more than the simple sum of their parts? Could we really make a self-assembling satellite composed of subassemblies of satbots that not only form structures but also serve .as "food," and even "see," "fly," and "talk?"

We intend to find out.

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Additional Reading

Valentino Braitenberg, Vehicles: Experiments in Synthetic Psychology, MIT Press, 1986.

Steven Strogatz and Ian Stewart, "Coupled Oscillators and Biological Synchronization," Scientific American, December 1993, pp. 102-130. Rodney Brooks' Web page. http://www.ai,mit.edu/people/brooks. html/.

RELATED ARTICLE: Modern Satellite Attitude Control Systems

Controlling the direction in which a satellite is pointed in space is a highly refined field of engineering that relies on a satellite's attitude determination and control system and also on communication from the ground. "Attitude" is a satellite's orientation in space.

Satellites move in orbits and can only change their orbits by changing their speeds. Satellites only cause themselves to spin around some axis if they generate torques. Hence, with torques satellites can reorient or repoint themselves as is necessary to counteract not only residual orbit-insertion errors but also natural environmental torques.

A satellite's attitude--in low earth orbit, for example--is calculated using three main types of sensors: sun sensors (coarse and fine) for finding the Sun, star sensors for locating major stars, and magnetometers for sensing Earth's magnetic field. The torques are supplied by actuators, such as chemical thrusters or magnetic torque coils and rods. A modern satellite attitude determination and control system typically consists of some combination of sensors, actuators, and computers. The computers run programs that process the sensor information, make a decision about what the attitude is and what it should be, and stimulate the actuators.

RELATED ARTICLE: Like a Metronome

Suppose all you want to do is orient a satellite so it keeps its solar panels illuminated by always pointing at the Sun by firming some thrusters. A conventional attitude control system executes millions of instructions per second reading the Sun sensors, makes many exact calculations, and then tries to send exact instructions to the actuators.

In contrast, our simple analog circuit made of just a few transistors, resistors, and capacitors acts like a metronome when you turn it on. It uses simple Sun sensors to control how long each tick and tock is, where each tick and tock controls a short thruster-firing cycle. If some error causes the control circuit to generate an erroneous tick or tock that causes an extra thruster firing, the circuit immediately goes back to its normal tick-tock pattern and automatically corrects for the erroneous thruster firing. Thus our analog circuit can calculate well enough to replace a more expensive and brittle digital computer.

RELATED ARTICLE: A Two-Neuron Controller

1. Each "neuron" at the heart of a satbot is composed of two primary components: a high pass filter and an inverter. The high pass filter ensures clean and sharp transitions between voltage levels, while the inverter forces the output of a single neuron to always be the opposite of its input (i.e., the output is zero volts when the input is +5 volts and vice versa).

2. The two neurons are arranged so that the output of one is the input of the other. Thus, if the voltage output of the first neuron is zero volts, the voltage output of the second neuron is +5 volts. This central pattern generator (CPG) is wired to a magnetic coil and sends currents to it. The currents go first in one direction, then in the opposite direction, hence making a magnetic field that reverses direction as the current reverses.

3. The coil magnetic field interacts with the ambient space magnetic field (typically

Earth's magnetic field) to produce torques that cause the coil to try to rotate first in one direction and then in the opposite direction. The amount the coil tries to turn is controlled by a pair of photodetectors connected in such a way that turning toward light is encouraged and away from light is discouraged. When the photodetectors are equality pointed at the Sun, the CPG locks into an oscillating state that remains, so long as the detectors are pointed directly toward the Sun.

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