COMMENT

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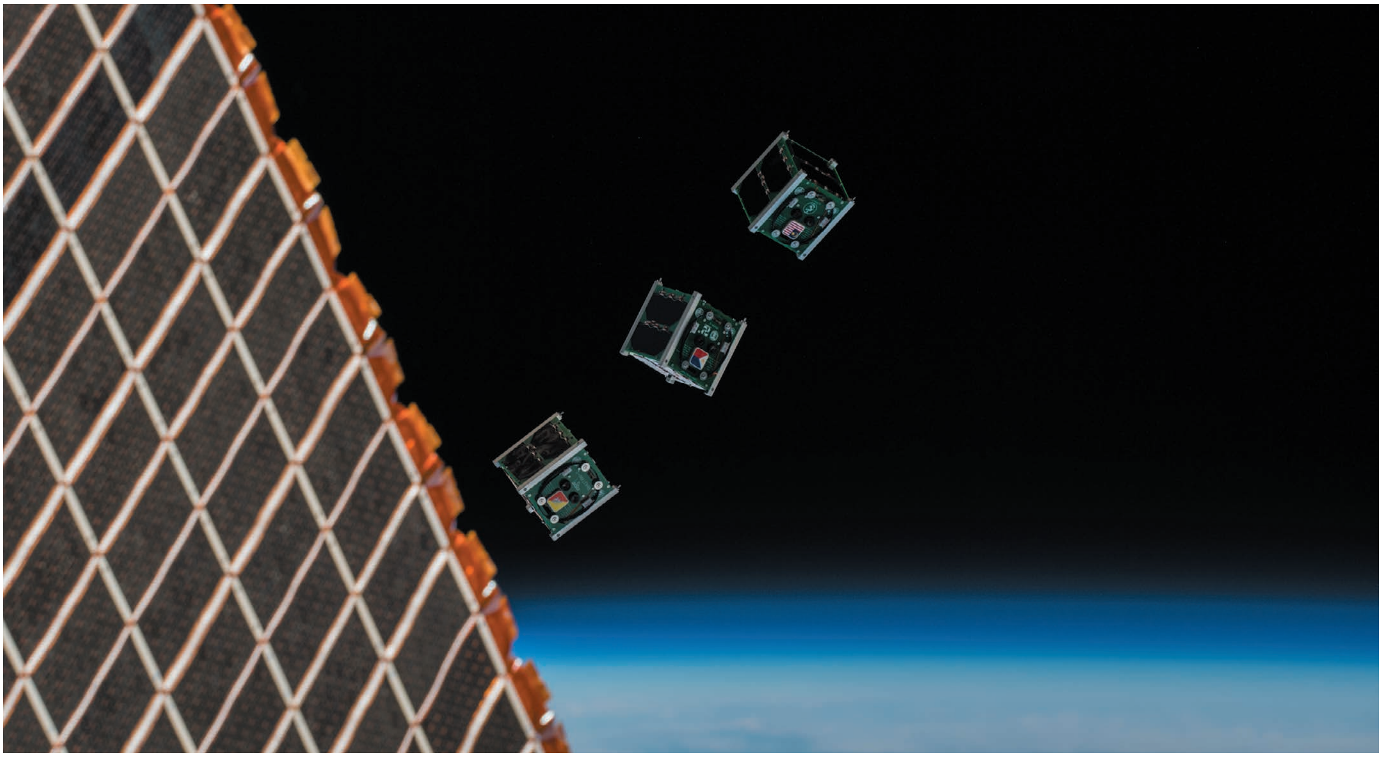


Three miniature satellites — CubeSats — launching into orbit from the International Space Station in August 2018.

Explore space using swarms of tiny satellites

Sand-grain-sized computers, self-healing materials and constellations of craft would reboot our reach, explain **Igor Levchenko**, **Michael Keidar** and colleagues.

"The first trillionaire will be made in space," US Republican Senator Ted Cruz told scientists and entrepreneurs in May at a Washington DC summit on sending humans to Mars. He could be right, but only if we rethink space technology.

The cost of launching a satellite is comparable with the value of its weight in gold. It takes thousands of dollars to send one kilogram into low Earth orbit, often ten times more than that. Returning material is even more expensive: it cost the equivalent of US$250 billion per kilogram of sample for Japan's Hayabusa spacecraft to bring back less than 1 gram of asteroid grains in 2010. The price tag for the whole mission was $250 million.

Still, space is big business. Globally, companies invested about $262 billion in 2016, mostly on using satellites for telecommunications, navigation and remote sensing[1] (see 'Lift-off'). Governments, too, spend billions — about $84 billion worldwide in 2016. More than half that ($48 billion) was from the United States, mainly for military, meteorological and communications purposes.

No one is getting much bang for those bucks. Space hardware has not kept pace with technology development and needs to be modernized. Satellites are still too bulky and expensive. Most perform only a limited set of predefined tasks. And, despite the skill and materials that went into them, they fail within decades — much more quickly than a Swiss watch.

At this rate, humans will never venture far from Earth, let alone colonize the Moon and Mars or capture asteroids.

Here we highlight three ways in which space technology needs to advance. Costs must be slashed; satellites should be small, ▶

▶ nimble and able to repair themselves; and they should operate in swarms.

MINIATURIZATION

Satellites are shrinking. More than 800 CubeSats are now in orbit. Made from palm-sized modules, these measure about 10 centimetres across and weigh only a kilogram or so. And researchers could soon be able to package the entire 'brain' of a satellite into 1 cubic millimetre. For example, in March, IBM demonstrated a computer the size of a grain of salt, containing 1 million transistors. The smaller such devices become, the less energy they need to run, and the lighter and cheaper they are to launch.

Satellites come in two types. Passive ones need only orientation and stability control. Active ones can be manoeuvred using thrusters. Passive satellites are easiest to miniaturize. We anticipate that they could weigh in at less than 100 grams if the hardware used for controlling stability could be made less bulky. Together, thousands of these 'femto-satellites' could operate as a network.

Active satellites would take longer to shrink. As Russian poet Vladimir Mayakovsky said (of mining radium), "For every gram you work a year." They would need minute propulsion systems. Electrical techniques are most efficient. These include: microcathode arc thrusters that use electrical arcs to convert solids into plasma; electrospray systems that generate microdroplets or ions; thrusters based on field emissions that produce energetic ions; and gas-fed systems, such as miniaturized Hall-effect thrusters, in which the propellant is accelerated by an electric field.

Standard designs of tiny satellites will be needed to speed up development, production and deployment, and to save money. But the designs must be customizable so that they can, for example, support bespoke scientific instruments and protect sensitive components from heating or irradiation when necessary. Many design templates will need to be pursued at once.

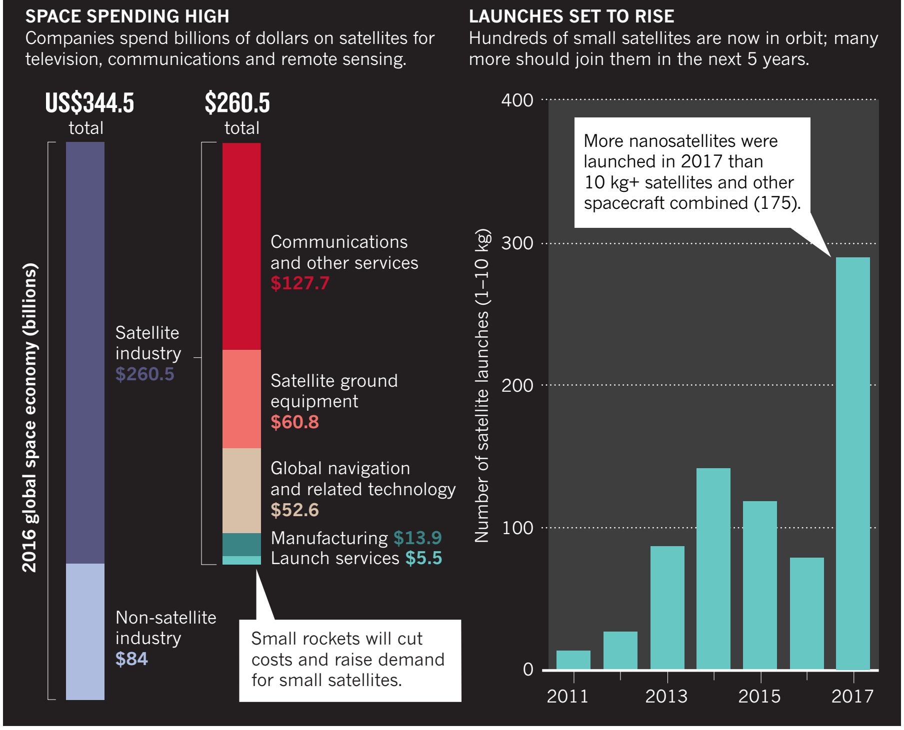
Tiny satellites need small rockets to launch them. Although industry interest remains strong for large carriers such as the Falcon 9 rocket (which is capable of carrying hundreds of small satellites as well as big ones), 'microrockets' are being developed by emerging companies such as Vector Launch in Tucson, Arizona (of which one of us, J.C., is chief executive), Firefly Aerospace in Cedar Park, Texas, and Gilmour Space Technologies in Queensland, Australia. Microrockets are relatively cheap and quick to make. They weigh a few tonnes — much less than the 500-tonne Falcon 9 or 733-tonne Delta IV Heavy. Small rockets fitted with small, simple engines (that use solid propellants) could deliver dozens of CubeSats at once to low Earth orbit, potentially daily.

LONGEVITY

Before we blast thousands of small satellites or interplanetary probes into space, we must ensure that they will keep working. A swarm of unreliable satellites faulting like bulbs in a string of lights would hardly be efficient. Longevity is crucial for colonizing the Moon and Mars, where equipment failure might mean life or death.

LIFT-OFF

Satellites make up three-quarters of the global space economy. They are being launched in record numbers as the costs of building and putting them into orbit come down.



SPACE SPENDING HIGH
Companies spend billions of dollars on satellites for television, communications and remote sensing.

Small rockets will cut costs and raise demand for small satellites.

LAUNCHES SET TO RISE
Hundreds of small satellites are now in orbit; many more should join them in the next 5 years.

More nanosatellites were launched in 2017 than 10 kg+ satellites and other spacecraft combined (175).

SOURCES: REF. 1 (LEFT PANEL); SPACEWORKS (RIGHT PANEL)

Today's satellites are typically designed to last for between 1 and 15 years. Some space technology survives for longer: the 41-year-old Voyager 1 probe left our Solar System in 2012, but it is unlikely to send us back a message 40,000 years from now, when it is due to pass near the star Gliese 445 in the constellation Ursa Minor. Satellites disintegrate quickly because space is hostile — extremely cold, almost a vacuum and peppered with high-energy particles and ionizing radiation.

Building in redundancy can only go so far. For example, the Curiosity rover on Mars was intended to work for about 500 Martian solar days (sols). It celebrated sol 2,000 in March — although it has small breaks on at least one of its six wheels. Adding spare wheels is an obsolete approach.

If satellites are to remain functional for a century or more, they need to be able to regenerate — as living organisms do. For example, the jellyfish *Turritopsis dohrnii* can rejuvenate almost indefinitely. Whenever it feels threatened or is injured, it reverts from its mature medusa state to the polyp state, thus beginning its life again. It can do this several times a year, depending on the environment. Some more-complex animals, such as axolotls (*Ambystoma mexicanum*), can grow new limbs, and microscopic tardigrades can survive in outer space.

Likewise, in space, human habitats, as well as tanks containing fuel and air, must be able to plug punctures and cracks autonomously. Batteries, electric generators and sensors should repair themselves when they are damaged. Some materials capable of self-healing have been developed in the lab, including flexible laminates, polyurethane composites, metallic materials and semiconducting polymers[2–4]. NASA recognized this need in its 2017 technology investment plan[5]. But a lack of collaboration between materials scientists and space technologists is slowing development.

Other types of advanced materials that are ripe for exploitation in space include durable and self-repairing lightweight and flexible structures for exploration and colonization missions. Materials with special heat properties are needed for spacecraft re-entering the atmosphere of Earth or other planets. Carbon-nanotube scaffolds, mimicking the nanoscale structures of sea shells, might increase the toughness of materials and improve ceramics. Strategies are also needed to stop cracks propagating and to prevent fatigue damage from accumulating. Environmentally friendly

A rocket built by US firm Garvey Spacecraft (now part of Vector Launch) carried four CubeSats in 2013.

NASA/DIMITRI GERONDIDAKIS

materials are desirable.

Researchers need to explore adaptation. Spacecraft might have to deal with the unexpected, such as grabbing irregularly shaped asteroids or handling other satellites for repair missions. Adaptable grippers, made from elastic or intelligent materials, need to be designed. Eventually, we'll need fully self-repairing space platforms, including propulsion systems, power plants, life-support systems and scientific instruments. Building even a prototype demands major breakthroughs and new ways of working.

NETWORKING

Instead of building one satellite to perform a single task, constellations of thousands of satellites have much broader potential. Their instruments can operate together as if they were on a much larger platform. For example, the five satellites that now make up the Afternoon Train constellation monitor clouds, aerosols and greenhouse and other gases in Earth's atmosphere to provide 3D reconstructions of climate and weather patterns and atmospheric pollution. In the CANYVAL-X mission, two CubeSats fly in formation to develop techniques that will help to study the Sun (one is equipped with a microcathode arc thruster).

Many configurations are possible — from trains of satellites following one another along the same orbit, to evenly spread networks watching Earth's entire surface (and, in future, maybe also those of the Moon and Mars). The constellation's shape can be adjusted. Several networks can be linked together virtually, to increase their power, resilience and responsiveness. Some satellites might be tooled to repair and adjust others.

Swarms of miniature satellites should be cheap and quick to deploy. Thousands could be released from a large central satellite in orbit. Swarms able to receive and send signals and perform basic logic operations could be combined with clusters of fewer, larger, more-complicated and manoeuvrable satellites that act as communications or analysis hubs.

Ultimately, constellations might behave like a neural network or artificial intelligence. Collective properties could be exploited, such as self-organization, transformability, self-learning and simultaneous sensing over a large area — as in the clouds of microscopic, interacting robots envisaged by Polish science-fiction writer Stanisław Lem in his 1964 book *The Invincible*.

So far, only tens of satellites have been strung together. The Global Positioning System (GPS) satellite constellation, for example, requires about 30 operational satellites for reliable global coverage. Efforts are afoot to increase the numbers. In Japan, Hokkaido and Tohoku universities have partnered with other organizations to send 50 microsatellites into space by 2050 (each weighing about 50 kg) to trace the aftermaths of natural disasters. The Iridium telecommunications network is being boosted to contain around 80 satellites.

By the mid-2020s, the company SpaceX intends to launch 12,000 small satellites to set up Starlink, a space-based Internet network. Two prototype Starlink satellites were launched in February, and the network may begin operating as soon as 2020. The communications company OneWeb aims to ensure affordable global access to Internet services through a constellation of 600–2,000 small satellites (up to 200 kg), with the first slated to be launched as early as December. Boeing's proposed constellation of 1,300–3,000 communications satellites is another example.

However, the satellites in most of these constellations are controlled from the ground. To operate efficiently, constellation units need to be able to communicate with each other and to adjust their positions and orientations in real time.

NEXT STEPS

Experts in advanced nano- and metamaterials and propulsion need to collaborate more to develop self-healing, regenerative materials for space applications. These range from composite materials for human habitats and large inflatable structures, to ultra-hard ceramics for thrusters. Micro-thrusters need to be more efficient and reliable. Unconventional systems, such as thin-film and 3D-printable thrusters, also need attention. This will require a continuing dialogue between materials scientists, propulsion experts and robotics specialists, which should begin in conferences on material advances in space technology, such as the International Conference on Micropropulsion and CubeSats (www.micropropulsion.org). Commercial companies will reap the benefits, and should contribute to the millions of dollars the research teams will need.

Mass-production methods must be optimized for delivering constellations of thousands of satellites. Additive manufacturing techniques such as 3D printing are lowering the costs of custom satellites. Production methods must be factored in when designing space technologies. Designs of auxiliary systems such as launch pads, thruster platforms and power and control systems must be standardized.

In addition, policymakers and lawyers need to develop an international legal framework for operating large constellations. For example, licences and permissions are needed to launch craft. Communication frequencies and orbits need to be assigned. The de-commissioning and removal of satellites at the end of their working lives must be coordinated internationally. Insurance needs to be established for losses from delays in the deployment of satellites, as happened for the Iridium NEXT mission to upgrade its constellation.

It is too soon to say whether the space economy will become profitable. But central to that economy will be the coming constellations of tiny satellites. ■

Igor Levchenko *is a research scientist at the National Institute of Education, Nanyang Technological University, Singapore.* **Michael Keidar** *is professor of engineering and founding director of the Micropropulsion and Nanotechnology Laboratory at George Washington University, Washington DC, USA.* **Jim Cantrell, Yue-Liang Wu, Hitoshi Kuninaka, Kateryna Bazaka, Shuyan Xu.**
e-mail: levchenko.igor@nie.edu.sg

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