NSR
NORTHERN SKY RESEARCH

A Superconducting Paradigm for the Satellite Industry

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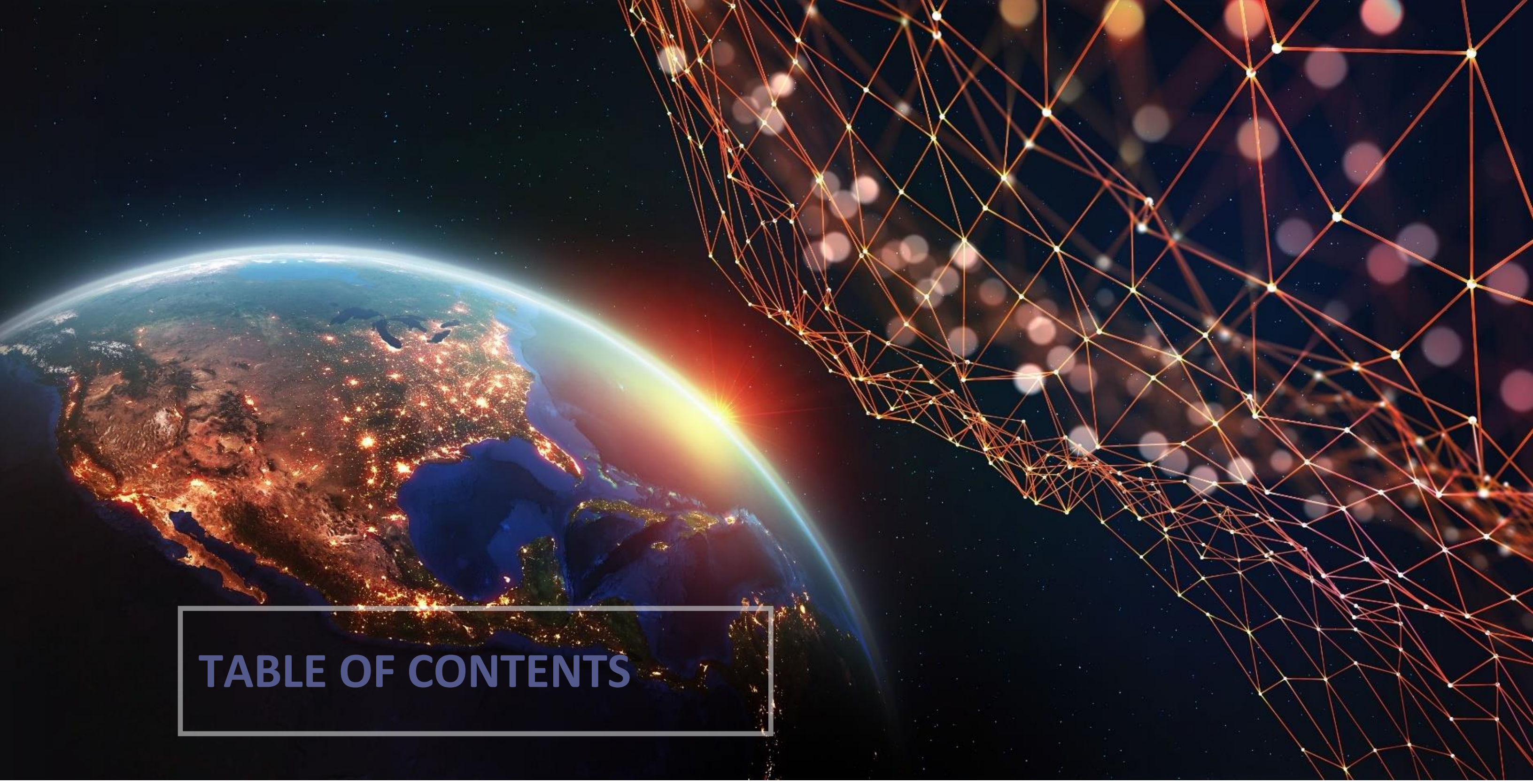

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INTRODUCTION

The global satellite manufacturing industry is an important component of the broader space economy. Its expansion has been fuelled by technological advancements, increased demand for communication services, and higher interest in lunar and Mars missions. We will delve into the various aspects of this burgeoning industry in this paper by looking at satellite manufacturing trends, market sizes for GEO (Geostationary Orbit) and Non-GEO satellites, and specific trends in mass classes. The overall picture will then guide us to understand better force-generating technologies like propulsion systems, thrusters, flywheels, and magnetorquers and how superconductors are playing an increasingly important role in the satellite industry for better performance of spacecrafts.

"Superconducting magnets generate exceptionally strong magnetic fields with unprecedented efficiency. It is through the power of super conductors that we at Zenno are delivering a new force in space, and we will continue to explore this force and develop multiple applications for the benefit of the entire space sector."

Hussain Bokhari

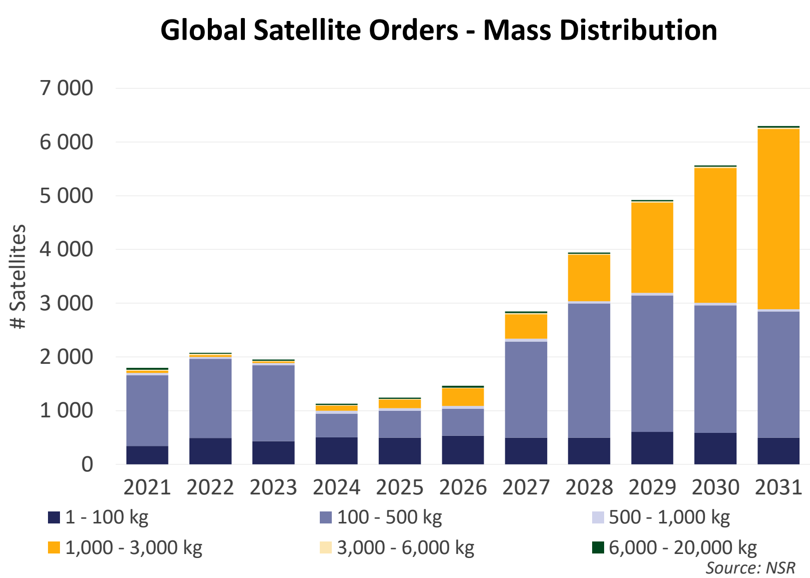
NSR, An Analysys Mason Company -Senior Analyst

Max Arshavsky with Z01

Zenno Astronautics - CEO

Satellite Manufacturing Trends

Satellite production is a multidisciplinary process requiring precision and great attention to detail. From component design and development to spacecraft assembly, integration, and testing, every aspect must be meticulously coordinated to ensure the finished product can withstand the harsh environment of space and execute its intended functions across a wide variety of missions.



Several trends have emerged in satellite manufacturing over the years as proliferation of systems via constellations has taken hold. A major driver is the rise of commercial space ventures and the miniaturization of satellite technology. What started as a CubeSat revolution in the late '90s has turned into a small satellites frenzy, with a growing number of smaller size class satellites launched into orbit. As satellite operators begin to address new demands from customers, the **100-500 kg mass range has become the most popular category and NSR estimates it represents 51% of the overall market** over the next decade, mostly for constellations**.**

A Shift in Satellite Masses

% of Mass Distribution	Current	Future
1 – 100 kg	19%	8%
100 – 500 kg	73%	37%
1000 – 3000 kg	2%	53%

Source: NSR

This trend is pushed forward by a transition to smaller satellite from customers such as the U.S. Department of Defense for the SDA's Proliferated Warfighter Space Architecture and commercial players such as SpaceX for its LEO Starlink constellations or Saturn Satellites for its GEO smallsats. However, towards the end of the decade, demand for larger mass categories will grow in response to increased capacity requirements demand on each spacecraft.

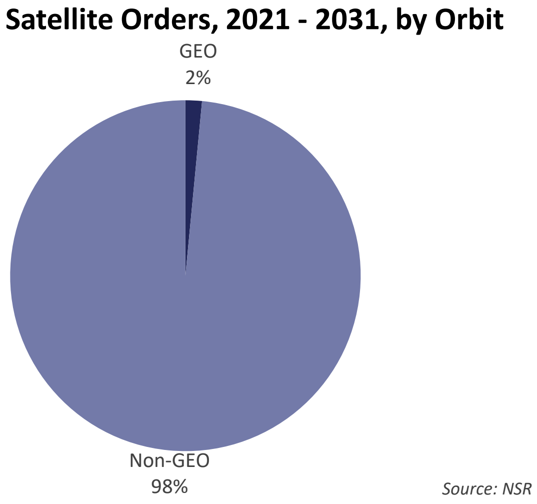
Another trend is the growing importance of satellite propulsion systems. Propulsion systems, thrusters, flywheels, and magnetorquers are all critical components of the design of satellites. Satellites can move in space thanks to propulsion systems, and thrusters help to fine-tune their position. In attitude control systems, flywheels are commonly employed to position the satellite, and magnetorquers, or magnetic torquers, provide an attitude control mechanism that does not rely on consumable resources. In very high orbits magnetorquers no longer provide enough torque and fuel-based solutions are instead used in their place.

This ability to maneuver a satellite in orbit greatly increases its useful life and functionality. Furthermore, fuel efficiency has emerged as a critical design factor. Radiation-hardened subsystems are also becoming more important as satellite operators juggle with shorter replenishment cycles in the harsh environment of space. Radiation protection for satellite components ensures longer operational lifetimes and reduces anomalies. These anomalies, which are frequently caused by radiation effects, technical issues, or space debris, are yet another important trend that is critical to address for satellite longevity and reliability to mitigate anomalies with robust design and manufacturing processes.

Finally, satellite lifecycle management is also an important trend, focusing on maximizing a satellite's operational life while also planning for end-of-life disposal to reduce space debris.

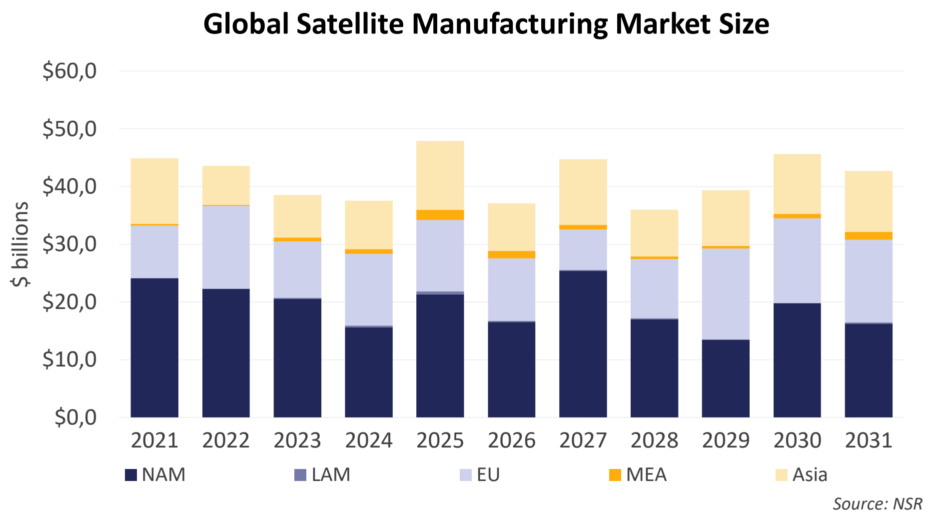
GEO and Non-GEO Markets Growing

NSR expects satellite manufacturing orders to reach over 33,000 and generate $457 B in revenues over the next decade. Because of their distinct applications, the market sizes for GEO and Non-GEO satellites vary significantly.



GEO satellites are mostly used for communications, weather monitoring, and broadcasting. NSR forecasts the **GEO satellite launch & manufacturing market to generate $69.4 billion** over the next decade, of which $52.1 billion will come from more than 500 GEO satellites orders expected between 2021 and 2031. GEO satellite markets have remained relatively stable, reflecting the maturity of its most common applications which is telecommunications.

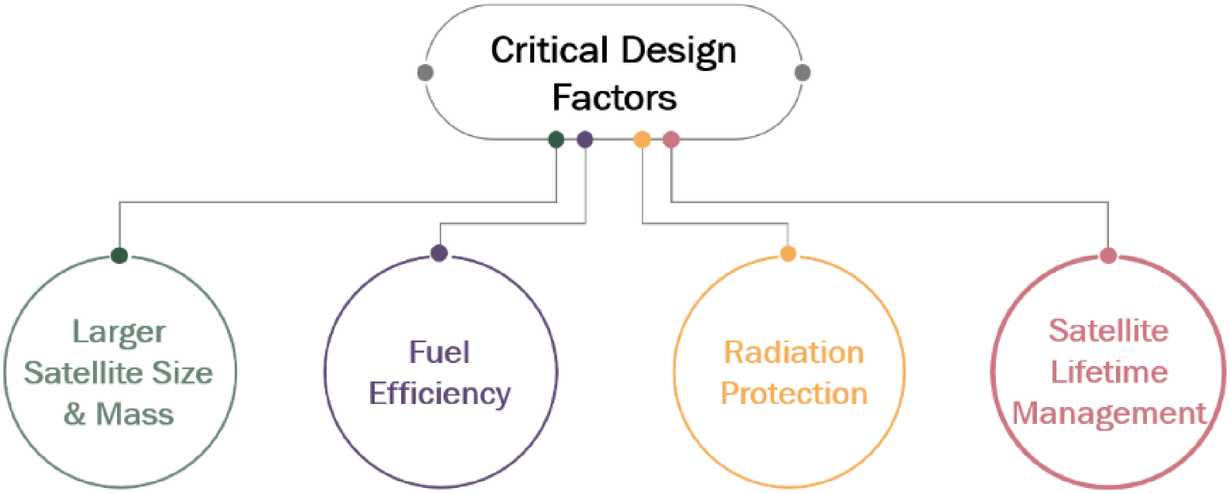
In contrast, the Non-GEO satellite market, which includes Low Earth Orbit (LEO) and Medium Earth Orbit (MEO), has grown at a breakneck pace. NSR forecasts over **32,000 Non-GEO satellites** to be manufactured with a majority ordered by satellite constellation operators. These **will generate $554.1 billion, from which $405.2 billion are from manufacturing**. The surge in small satellite launches for earth observation, scientific research, and broadband communication services is driving this growth coupled with a rise in mega-constellations such as SpaceX's Starlink which has expanded the non-GEO market even further.



Mass Class Trends

As we noted, capabilities per spacecraft is a driver of demand for larger mass class satellites and spacecrafts. Furthermore, Crew & Cargo and Lunar missions will add to this picture as well as commercial space stations that are in the planning stages. Several factors have contributed to this shift towards larger satellites. For one thing, technological advances enable more sophisticated payloads and subsystems, thereby increasing their size and mass. This is seen in the demand for satellites capable of supporting higher bandwidth communications, Earth Observation imaging payloads, and advanced scientific research on larger satellites capable of meeting such demanding requirements.

Another factor is the increased emphasis on satellite endurance and robustness. Satellites must be equipped with durable materials and systems to withstand the harsh space environment for extended periods of time, which invariably adds to their mass. However, the shift to larger satellites introduces new challenges, particularly in terms of launch and operation. The force-generating systems are thus becoming critical in maintaining a long lifetime to amortize the investments and keep a satellite's orbit, orientation, and attitude.



A review of existing satellite force-generation technologies such as propulsion systems, flywheels, magnetorquers together with the presentation of a new revolutionary technology that will shift the paradigm of how satellite maintenance is at stake today.

- Propulsion Systems

The propulsion system of a satellite is its primary means of motion and control. Effective and efficient propulsion systems become even more critical as satellites grow. They help position the satellite in its designated orbit and maintain its correct orbital path for proper operations. Larger satellites need more powerful propulsion systems to counteract the increased gravitational pull caused by their mass. Propulsion systems come in a variety of configurations, ranging from traditional chemical thrusters to cutting-edge electric propulsion. Chemical propulsion generates a large amount of thrust, making it ideal for large satellites. It does, however, consume a lot of fuel. Electric propulsion, on the other hand, such as Hall effect thrusters and ion thrusters, is a more fuel-efficient option, providing small but continuous thrust. They are especially useful for long-duration missions as well as precise positioning and control of large satellites and to save mass, which is a cost driver of launch costs.

- Flywheels

The attitude control system that adjusts the satellite's orientation in space is another critical component of a satellite's force generation technology. These systems must be more robust for larger satellites to handle the increased moment of inertia for which flywheels or reaction wheels are most used. These mechanical devices store rotational energy, and changes in their spin speeds produce torques that orients the satellite without the use of propellant. They are especially useful for fine-tuning a satellite's attitude and sustaining control over lengthy periods of time. However, flywheels have a few drawbacks. They saturate, which means that if left uncontrolled, they will reach their maximum speed and be unable to produce any more torque. To discharge the momentum in these cases, an additional apparatus is necessary. Additionally, their moving parts can cause mechanical breakdowns over time.

- Magnetorquers

Magnetorquers, also known as magnetic torquers, are another method of attitude control that is especially useful for low-Earth orbit satellites. These are typically used in tandem with Flywheels. They produce a magnetic dipole, which interacts with the Earth's magnetic field to produce torque. Coil-based magnetorquers are widely used, in which an electrical current is supplied through a wire coil to generate a magnetic field. Rod-based magnetorquers, on the other hand, use a ferromagnetic rod that becomes magnetized in a magnetic field. Because of their simplicity, dependability, and absence of consumable resources, these systems have several advantages: they are ideal for dumping momentum from flywheels and serving as a backup attitude control system. Magnetorquers have several disadvantages. Firstly, their Size, Weight, and Power (SWaP) is poor, scaling linearly and making them bulky and cumbersome for all but very small satellites (and totally impractical for some missions).

Also, their effectiveness declines dramatically in areas with a weak geomagnetic field (higher orbits, particular orbital inclinations). Furthermore, they can only create low levels of torque and over short periods of time as electrical resistance in their wire causes heating. These factors combine to make them unsuitable for abrupt attitude changes.

Flywheels and magnetorquers are essential for controlling larger, heavier satellites. As satellite mass increases, these force-generating technologies will undoubtedly become even more important in satellite operation.

Zenno Astronautics Limited

Zenno is a New Zealand and US based company, founded in 2017 and is the global leader in the use of super conducting magnets for space. The Zenno team offer resolution to a significant number of currently unsolvable problems for commercial and public sector spacecraft manufacturers.

Generation and control of force in space is the crucial factor in the operation of spacecraft and satellites. Technologies exist for generating force (flywheels, magnetorquers, thrusters) but as previously noted these all have drawbacks. These drawbacks include power consumption, reliability or simply the need for an expendable fuel. Superior operation in space is achievable if a system that generates force, perpetually, and across a wide range of orbits and mass-class requirements, could be developed.

Z01, a 3-axis superconducting torquer

This idea of propellant-less (note, not reaction-less) force generation system is the original driver behind Zenno's technology, this is the task Zenno set itself to solve for the space industry. Over the last 5 years Zenno has invented a patented platform of technology that is acutely relevant to multiple existing and emergent space applications. A powerful magnetic field would interact with the Earth's magnetic field (or that of nearby satellites or other celestial bodies) and counteracting forces generated by flywheels would then allow force generation.

Generating these fields requires enormously powerful magnets and Zenno's initial work identified superconductors as the ideal solution due to their ability to sustain unprecedently high electrical currents with near zero energy loses.

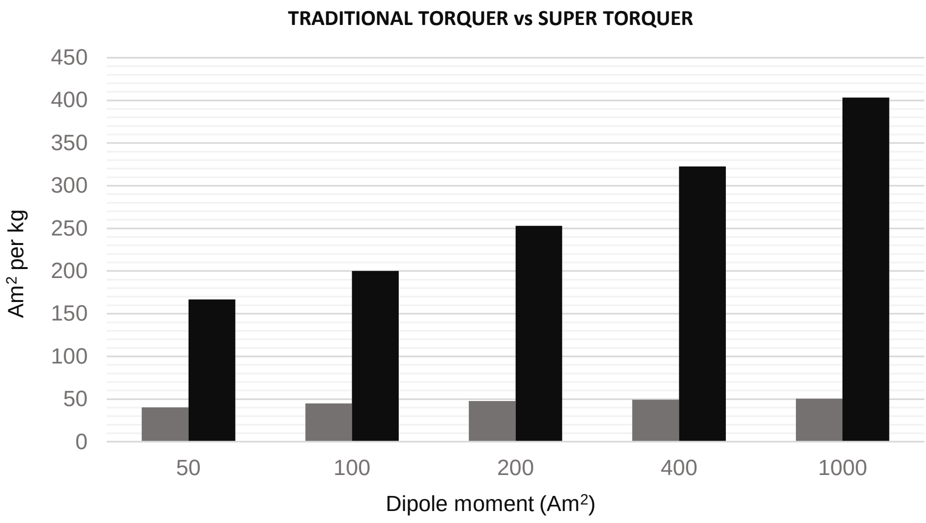
This research has now matured to include a broad range of applications that require powerful and precise control of force in space: attitude control, docking, satellite swarms and even orbit boosting by other physical means.

- Competing technologies have been developed to achieve force control and generation, such as flywheels, thrusters, magnetorquers etc.
- These technologies were developed decades ago.
- We saw an opportunity to generate force in space using very new science, high temperature superconductivity.
- This technology is the only one known that can generate force across multiple application areas.

Zenno Technology

To achieve the aims, several logical but disparate concepts were combined, the Zenno approach includes liquid cryogen-free thermal management and wireless energization of the electromagnets and doing the entire process in space. Combining all these ideas has resulted in devices with a far superior size, weight and power to both classical magnetorquers/electromagnets and with flexible form factors that enable new design approaches.

These advantages are particularly relevant in the expected future mass classes mentioned previously (51% in 100-500kg), where Zenno tech can easily produce the torque required in a SWaP envelope that is far superior to the traditional technology (Figure 1).

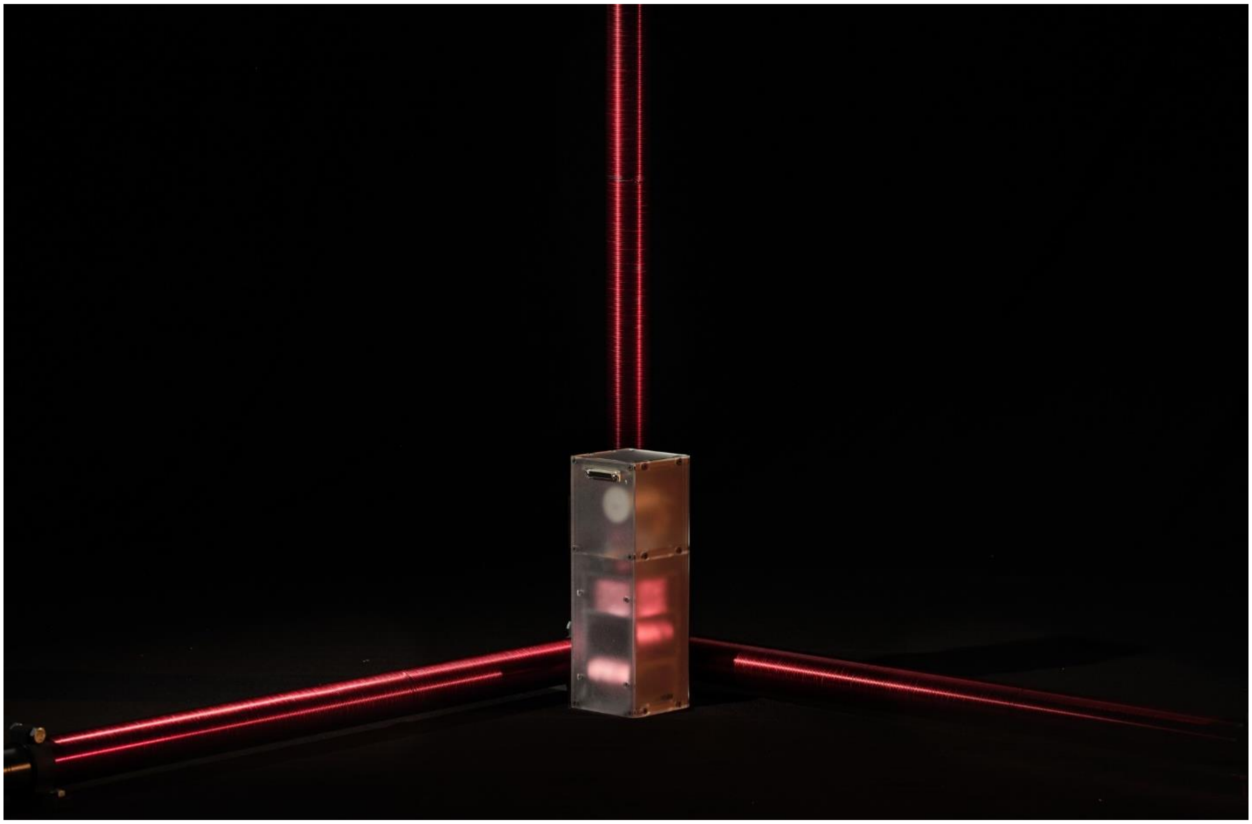


A significant factor in the development of Zenno technology has been that our interest has been focused exclusively on space-based applications. Ground-based applications of superconductivity focus either on exceptionally large current (power generation/transmission) or exceptionally strong fields (MRI, industrial/research applications).

Outclassing Existing Markets via Zenno Technologies

The most immediate industry applicable use case of this new high-temperature superconducting (HTS) technology is in satellite attitude control (ADCS), as a replacement for traditional magnetorquers, or fly wheels or thrusters.

The performance of the Zenno's superconducting magnetic torquer scales non-linearly and by 100 Am^2, the Z01, the product name of the Zenno device, is less than ⅓ the size, weight, and power (SWaP) of comparable traditional magnetorquers.



Conventional torque rods vs equivalent Z01 3-axis dipole system

Beyond ADCS, our HTS technology is in the development phase to provide final approach and docking capabilities via magnetic docking. The lack of propellant and the nature of the magnetic fields makes this a more automatable and safer procedure than current approaches (gas-thrusters, robot arms). Magnetic docking is a more complex but logical step from ADCS with additional components and control required.

Creating and Extending Upcoming Markets via Zenno Technologies

Extending the scale of our devices to larger regimes allows operation at greater inter-satellite distances (100+ meters). This would then enable applications such as swarm operations and full-range docking, the latter of which is a requirement for in-orbit construction.

Magnets scaled to multi-Tesla and/or 1,000s of Am^2 could be used to shield satellites and spacecraft from space weather via magnetic radiation shielding, which will enhance satellite and endurance (as mentioned in previous sections). More sophisticated systems can be used to accelerate satellites to other orbits and control high-energy plasmas (spacecraft re-entry, fusion, & thrusters).

We have a clear technology development pathway identified that will allow us to evolve Zenno's technology platform to enable these applications for the immediate and long-term benefit of commercial and public sector spacecraft manufacturers.

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