An Air-Levitated Testbed for Flux Pinning Interactions at the Nanosatellite Scale

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Magnetic flux pinning interactions have been recently demonstrated as viable mechanisms in modular spacecraft reconfiguration maneuvers. However, in order to develop a robust testing program for interactions, a low-cost testing environment is necessary to simulate the microgravity environment in which this technology will ultimately perform. The FloatCube testbed we have developed to support this effort is built around uniform free-floating test vehicles with a set of planar air bearings that provide two translational and one rotational degree of freedom. The vehicles allow for rapid implementation of new experiments by providing a standard levitating base segment and optional power, communications, and control components to support experimental actuator and sensor arrangements. The system is also designed to support current and future flight missions and microgravity tests by mounting completed nanosatellites or nanosat-sized modules on individual vehicles capable of operating independently or in formation in concert with a computer interface. This paper presents the design and implementation of the FloatCube system, ongoing work with experimental verification, and future work expected to improve the testbed and verify mission hardware.

Nomenclature

\[ FPI = \text{Flux-Pinned Interface} \]
\[ DOF = \text{Degree of Freedom} \]
\[ HTSC = \text{High-Temperature Superconductor} \]
\[ T_C = \text{Critical Temperature} \]

I. Introduction

FLUX pinning is a well-known phenomenon that establishes a non-contacting connection between magnets and superconductors. It has recently been studied as a potential mechanism for the construction, reconfiguration, and docking of modular spacecraft via a flux-pinned interface (FPI). Modules linked by a FPI are capable of passively maintaining a prescribed relative position and orientation while resisting disturbances. These properties make FPIs an attractive option for spacecraft applications. Flux pinning has also been proposed as a reconfiguration mechanism for modular spacecraft assemblies. FPIs that allow motion in only certain degrees of freedom (DOF) can form virtual joints between spacecraft modules. The system can then reconfigure through the movement allowed by the flux-pinned joints.

Flux pinning occurs when magnetic field lines induce small current vortices in the superconductor material, causing the magnetic field lines to become “trapped” on material impurities, which results in a resistance to changes in the magnetic flux. This interaction happens only below a certain critical temperature \( T_C \), which is about 80 K for high-temperature superconductors (HTSC) such as YBCO commonly used for flux pinning. When the superconductor is cooled below \( T_C \) in the presence of a magnetic field, the magnetic flux lines imprint the current position and orientation of the magnet and the superconductor into the superconductor's material. This process, known as field cooling, forms the basis for the FPI. The magnetic field source is pinned to the HTSC in such a way that the interface resists perturbations from the equilibrium via a nonlinear restoring force. Once the FPI is established, the connection between magnet and HTSC is passively stable, requiring no active control or added

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energy (in the case of permanent magnets) to keep the system in the established equilibrium arrangement. One common application of flux pinning is magnetic levitation in 1 g, as shown in Figure 1.

The FPI can exhibit stiffness and damping in six degrees of freedom (6DOF), resisting any relative motion of the system components. With an axisymmetric field, however, some DOFs can be left free. When such a magnetic field is generated by one spacecraft module and a superconductor flux-pinned to that field is mounted on another module, the FPI can function as a revolute joint. Previous work in this area has confirmed that flux pinning can create joints and other mechanisms, some of which have been validated in both laboratory experiments and during microgravity testing. These mechanisms, when deployed as links on a close formation of spacecraft modules, could allow the spacecraft to easily reconfigure via ground-based commands to electromagnets.

Standard laboratory experiments of spacecraft components (such as the flux-pinned mechanisms previously demonstrated) face the challenge of operating in a test environment that is dissimilar to the conditions present in a space environment, particularly with regards to gravity. High-precision systems found on satellite hardware that require a low-torque environment are often overcome by the typical forces encountered in an earth environment, making it difficult to validate their functionality. Many solutions exist to address this problem, some of which are more suitable for certain applications than others. Neutral buoyancy testing in a water tank may be useful for testing components on a manned spacecraft mockup, but might be prohibitively difficult for a nanosatellite formation. One possible solution is the use of air bearings, which can provide a minimal-torque environment to test equipment in certain DOF. Air bearings have been used to test spacecraft attitude determination and control concept verification for over 45 years, providing some combination of nearly torque-free rotation and force-free translation.

Air bearings function by forcing pressurized gas through small holes in the bearing face adjacent to a smooth test surface. This pressure establishes a thin film of gas that supports the test vehicle above the surface and acts as a lubricant that allows for extremely low friction movement of the bearing over the surface. Two primary types of air bearings are commonly used: planar bearings that provide one rotational and two translational DOF, and spherical air bearings that provide rotational motion constrained only by equipment affixed to the bearings. Test facilities using a variety of equipment based on air bearing levitation exist for testing spacecraft and satellite components.

One familiar example is the use of an air hockey table to support a mock spacecraft test vehicle. A previous experiment used this setup to demonstrate a flux-pinned revolute joint, shown in Figure 2. This method had several drawbacks, however, including a low mass limit on floating vehicles and a large flow rate of high pressure gas to provide sufficient output over the entire table surface. These limitations provided incentive for us to design a new testbed and make it more robust to allow more complex maneuvers in equipment testing.

We have designed a new testbed that addresses both weaknesses of the previous system and specific concerns for ongoing research in flux pinning interactions. The FloatCube testbed is based upon the CubeSat size scale as a practical method of demonstrating our flux pinning concepts. A 10 cm standardized cube structure, the CubeSat has a low launch cost and prebuilt components available to support experimental hardware, making them an ideal platform for small spacecraft research projects. Each FloatCube vehicle is supported by a self contained planar air bearing system, providing levitation for experimental hardware and test equipment. The FloatCubes are made to fit CubeSat-sized modules for testing as well as our newly fabricated joints.

Figure 1. A permanent magnet flux pinned above a HTSC which has been cooled below Tc

Figure 2. Air table and vehicles used to verify flux-pinned revolute joint.
developed half-cube designs used for microgravity flight testing and can support a many configurations of experimental hardware at the nanosat scale. Like the CubeSats, FloatCubes are designed to be relatively inexpensive and easily accessible to universities and other small research groups. By combining multiple FloatCube vehicles, we can construct a system of multiple independent vehicles to investigate interesting reconfiguration maneuvers.

This paper presents the design and details of the FloatCube testbed, highlighting significant system components essential to meeting our desired performance. It describes the range of experiments supported by FloatCubes, specifically the interface with microgravity testing and compatibility with CubeSat flight hardware. Previous and ongoing research in flux pinning interactions performed using FloatCube vehicles are documented along with proposed applications that could use the FloatCube testbed for verification.

II. System Architecture

The FloatCube testbed system architecture is detailed in Figure 3. The basis of the testbed is that each module or spacecraft in the desired formation is supported by an individual FloatCube vehicle and together they serve as a mock nanosat with unrestricted planar motion. Each vehicle can provide levitation above the testbed surface for its mounted experimental components through the use of air bearings with an onboard gas supply. The vehicles are composed of several segments, each serving a different function, physically stacked together and levitated above a surface designated for FloatCube testing.

A. Testbed Hardware

The testing surface can be any smooth surface suitable for air bearing use, including highly polished granite, poured plastic, or, as is used in our current configuration, plate glass. It is also important to ensure the testing surface is flat to prevent a gravity gradient from causing the vehicles to slide from rest. Other experimental conditions can be introduced by intentionally changing the testing surface to a non-flat orientation. A potential field, for example, can be applied to the system by changing the angle of the testing surface with respect to the local gravity vector.

Supporting the experimental payload and vehicle itself above the testing surface are several planar air bearings, contained in the levitating base segment. This segment of the FloatCube vehicle also contains an onboard gas supply that allows the FloatCubes to move independently of outside tube or hoses that might impart forces on the vehicles.

Multiple types of experiment hardware payloads can fit on a FloatCube by using a variety of payload segment configurations. Loose experimental components, half cube microgravity modules, or full CubeSats can fit onto

![Figure 3. System architecture diagram illustrating interactions between FloatCube vehicles (more can be added with similar connections as Vehicle 2), individual segments and other test equipment. Each FloatCube contains only one of the three types of payload segments shown here in yellow.](image-url)
payload segments made specifically to fit their physical profiles. The satellite structures used for microgravity testing and flight hardware generally contain their own internal power supply and communications systems and do not require an additional segment to perform these functions.

To perform more preliminary experiments with independent actuators and other single components, the FloatCube can mount an electronics segment containing a power supply, microcontroller and Bluetooth module to link to a computer and allow remote control of the components mounted on the FloatCube payload segment. The FloatCube vehicle assembled from these segments levitates above the smooth glass testbed surface and provides two translational and one rotational unconstrained DOF with the array of planar air bearings in the base segment. The positions of FloatCube vehicle are tracked during their maneuvers through a motion capture camera and/or through recording of sensor information transmitted back to the computer by components onboard the individual vehicles.

B. Data Acquisition and Computer Interface

Several methods are available for sensing and data acquisition. Independent cube segments used often mount their own sensors that provide experimental data. By adding simple tracking points of high contrast (e.g. reflective tape) to the FloatCube vehicles a high speed camera can record position data and a time history of the vehicles during the experiment, which can be used to obtain other information of interest. The electronics segment can also be fitted with one or more sensors to provide measurements to the computer during an experiment. As flux pinning requires at minimum two physically separate components (one magnetic field source and one superconductor), the FloatCubes have been designed as independent vehicles that can be simultaneously deployed to allow flux pinning interactions. A simple experiment type features a fixed component interacting with one mounted on a FloatCube that allows relative motion in the system. Multiple FloatCube vehicles can also be deployed to investigate multi-vehicle interactions. Each vehicle can communicate with the computer to record experimental data and can, depending on the payload equipped, interact with other vehicles through onboard actuators. The number of FloatCube vehicles that can be added to the testbed is only limited by the testing surface area, communications bandwidth, and available hardware for constructing vehicles.

III. FloatCube Vehicles

Each FloatCube vehicle consists of two or three segments: the levitating base segment, which uses air bearings and an onboard gas supply to support the vehicle and provide unconstrained motion, the payload mounting segment, which can fit experimental hardware or assembled flight hardware for experiments, and the optional electronics segment, which can provide power, control, and connectivity with a computer system if necessary. These segments allow each vehicle to be self contained, allowing single vehicle experiments or multiple vehicle formations with identical supporting hardware. Used in conjunction with the testing surface, motion capture camera, and computer system, the FloatCube vehicles can accommodate all of our ongoing and prospective flux pinning experiments at a nanosat scale.

A. Levitating Base Segment

The base segment of the FloatCube vehicle provides the experimental hardware with a minimal-torque environment and freedom of motion in two translational and one rotational DOF. Figure 4 details the individual components that make up this segment of the vehicle. Levitation is provided by an array of three air bearings on the bottom of the segment, adjacent to the testing surface. Air-powered levitation for previous flux pinning experiments was accomplished with the use of an air table which raised experimental vehicles above its surface for unconstrained motion. The primary limitation of this arrangement was that a surface large enough for desirable maneuvers required a prohibitively high input pressure of gas to provide sufficient pressure over the entire surface to support the vehicles. In effect, most of the input gas was not used to support experimental vehicles but expended over empty surface area. The air bearings address this problem by shrinking the gas output area to the footprint of the individual bearings. The significant components used in this system are listed below:

- Air bearings (3) mounted on spherical joints;
- Pressure gauge;
- Pressure valve;
- CO₂ Cartridge, 12 or 16 g (2);
- Gas regulators and cartridge sleeves.
Each FloatCube base features an array of three New Way 12x24mm air bearings evenly spaced on the bottom of the base segment plate to provide stability and lifting power to the vehicle. Pressurized gas exits the bearings through a flat, porous membrane that is planar to the testing surface. This arrangement is shown in Figure 4 (a). When the vehicle is resting on the air bearings, they are connected to the base plate via spherical joints on each of the bearings. This arrangement allows the bearings to rest parallel to the testbed surface and align correctly. Even small misalignments between the surface and bearing film surface significantly reduce the lifting capacity of the bearings so spherical joints are crucial to FloatCube operation. The bearings are also attached to the base segment plate with two long screws. These connections do not restrict the motion of the spherical joint when the bearings are resting on the test surface but keep the bearings attached to the base plate when the vehicle is lifted vertically.

Mounted on the top of the base segment plate is the gas supply and regulation system. A diagram of the gas system currently implemented on the FloatCube base segments shown below in Figure 5. Two standard CO₂ cartridges provide a pressurized gas supply to the air bearings, chosen due to their availability, small size, and low cost. Both standard 12g and 16g CO₂ threadless cartridges can supply the system using adjustable gas regulators and cartridge sleeves from Genuine Innovations. These regulators can adjust supply pressure between 15 and 150 psi. Luer lock connection switches and the adjustable regulators allow easy manipulation of the gas flow to the bearings and replacement of exhausted cartridges. The New Way bearings operate between a range of 60 and 80 PSI, and flow rate can be easily observed through an onboard pressure gauge. The three bearings supporting the vehicle can lift over 11kg, allowing any payload in the nanosat range (typically 1-10kg). Using two 12g CO₂ cartridges, the FloatCube has about 14 minutes of levitation time to perform experiments. This increases to nearly 20 minutes with two 16g CO₂ cartridges. Experiment time can be maximized by using the pressure valve to allow gas flow only to the bearings only when experiment setup procedures are complete.

The structure of the base segment is also significant in the modularity of the FloatCube vehicle. A fully constructed FloatCube base segment is shown in Figure 4 (b). Once assembled and tested, the gas system requires little effort to support new experiments. The experimenter only needs to insert new CO₂ cartridges and allow the air bearings to align themselves on the test surface to enable FloatCube levitation. The gas cartridges are secured to the base plate with small aluminum collars that connect around the regulator circumference, which then slide into a slotted block of material that is mounted to the vehicle. This provides adequate space for the tubing connecting the gas system components and accessibility for changing gas
cartridges. Posts extending up from the base segment plate provide support for the experiment-specific payload and electronics segments. These segments can be securely attached with quick release pins to the base, also allowing their rapid removal to facilitate replacement of exhausted gas cartridges or the mounting of a new experimental payload.

At approximately $130 each, the air bearings are the most expensive component in a FloatCube vehicle. The gas regulators are $50 each, while other gas system parts range between $10 for the pressure gauge and the valve and $0.10 for tubing and corresponding connectors. Gas cartridges will incur a small recurring cost as they must be replaced after each run of testing. The physical structure of the base segment can be easily machined from metal or plastic stock.

B. Experimental Payload Mounting Segment

Because current flux pinning research involves hardware in various states of development, the experimental payload mounting segment was designed to maximize ease of use for each type of hardware likely to be mounted on the FloatCube vehicles. Given current research goals, three configurations of the payload segment have been developed to mount different types of hardware. The first configuration is designed to accommodate preliminary experiments with breadboard-level components. These components can be easily attached to the payload mounting plate and are accessible for rearrangement as the experiment progresses. Typical components in this type of flux pinning experiment are individual parts or arrays of magnets, electromagnets, superconductors, and sensors. An example of this configuration is shown in Figure 6 (a).

The second payload mounting segment configuration is designed to fit two half cube test modules. The half cube module is based on the CubeSat 1U (10x10x10cm) satellite structure and adapted specifically for use in microgravity testing. Microgravity test flights, such as those offered through the NASA Facilitated Access to the Space Environment for Technology Development and Training (FAST) program, allow an accurate microgravity test environment but impose unique constraints on experimental equipment. Previous flight experience guided the design of the half cube concept to specifically address these constraints. The features of the half cube design that are most relevant to the FloatCube testbed is the interface where two half cubes slide together to form a single cube of 15cm sides (slightly larger than the 1U CubeSat to allow for breadboard components rather than smaller flight-level hardware). This interface is replicated on this type of payload mounting segment, so the half cubes can be secured on the FloatCube. Figure 6 (b) illustrates how half cubes can be mounted through the sliding interface.

The final type of payload currently supported by the mounting segment is a full CubeSat structure. Flight projects based on CubeSat structures share a common size, making standardization of test equipment over several projects simple. A mockup or flight-ready CubeSat can be mounted on the third design of the payload mounting segment using brackets, as shown in Figure 6 (c), and verified before deployment. Larger CubeSats of 2U and 3U size (10cm² base area with 20cm and 30cm height, respectively) can also be tested by using multiple FloatCube vehicles to support their larger sizes.

Due to the relatively simple nature of the base hardware of the mounting segment, the only direct costs for manufacturing here are the stock and price of machining. Components for actual experimentation can be taken directly from other testing setups. Multiple payload segments may be necessary for mounting a variety of experimental components.

Figure 6. Payload segment (a) in component mounting configuration (with attached electronics segment); (b) with half cube modules; (c) with a CubeSat mockup.
C. Electronics Segment

For experiments not yet at the self-contained module level, additional capabilities can be added with the use of the electronics segment. This segment of the FloatCube is generally equipped with batteries capable of supplying up to 18V, a breadboard for mounting experimental circuitry, and an Arduino microcontroller with a Bluetooth connection to communicate with a computer interface. Based on payload requirements, this segment can easily be customized further from the baseline configuration. The standard electronics segment is shown in Figure 7. This segment fits into the component-based payload mounting segment, elevated above 10cm to provide the full CubeSat volume for experimental components. The Arduino microcontroller’s onboard Bluetooth connection provide an interface between sensors mounted on the FloatCube vehicle, experimental circuitry, control laws to govern actuator behavior, and an existing computer user interface. By constructing this flexible environment to support electronics and computer input, new electronic components and control strategies can be implemented with a minimum of effort to the existing interface.

The Arduino BT microcontroller costs approximately $100, encompassing the majority of the cost for this segment. Depending on the payload, the electronics segment can often be replaced with onboard power and communications, negating the need for the additional components of this segment. When supporting a component-based payload, the electronics segment can be easily reconfigured to support multiple experiments.

IV. System Operation

Though the FloatCube testbed was originally designed to meet the requirements for testing flux-pinned interfaces, the capabilities of the fully implemented system allow it to accommodate other nanosat-scale hardware for planar 3DOF testing. Analysis of the system in its current configuration and experimental verification of several vehicles have produced operational parameters that govern the range of experiments the FloatCubes are capable of supporting. These parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1 FloatCube Vehicle Operational Parameters</th>
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<tr>
<td>Mass supported by air bearings</td>
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<tr>
<td>Payload mass capacity</td>
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<tr>
<td>Mean time of gas supply (2 16g)</td>
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<tr>
<td>Operating pressure</td>
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<tr>
<td>Coefficient of static friction (on glass)</td>
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Before each FloatCube is ready for use supporting an experimental payload, several steps can be taken to ensure optimal levitation performance. Once the gas system components are connected by tubing, a leak check should be performed to ensure no gas is escaping before reaching the air bearings. Submerging the base segment in water while the system is engaged will allow the experimenter to easily determine if gas is leaking from the system and will not harm the bearings so long as the system is pressurized. To maximize the available experiment time for a set of gas cartridges, both should be connected to the system simultaneously and the valve should only be opened to the bearings once this is complete. Before beginning an experiment, the air bearings should be gently wiped with alcohol while discharging gas to remove any debris from their surface that might impede smooth levitation. The testing surface should be likewise cleaned. Small variations in pressure are to be expected as the cartridges discharge, so the regulators should be set to approximately 70 psi to keep the supply pressure within the air bearings’ optimal operating range.

The manufacture of the segment structure is also important to facilitate FloatCube vehicle operation. Sufficient space must be left for the air tubing to move freely as the air bearings align themselves to the testing surface, as contact between tubing and structural components can impart undesirable forces on the bearings and interfere with experiment actuation. The center of mass for the current configuration sans payload is approximately at the center of the machined gas cartridge holder block. To reduce the empty vehicle mass and increase possible payload limits,
lighter materials such as plastics can be used for much of the structure in place of the aluminum shown on current vehicles.

V. Experimental Applications

The FloatCube testbed as a whole consists of one or more FloatCube vehicles, a supporting test surface above which the vehicles levitate, a motion capture system, and a connected computer capable of acquiring sensor input or implementing control laws. These components have allowed for testing in two distinct types of flux pinning investigations. Experiments that involve the design of general flux pinning mechanisms, such as a revolute joint or four-bar linkage, commonly focus on single flux pinning interaction. For an upcoming flight mission or microgravity test, module verification is necessary to ensure the assembled system will work as expected when deployed. The FloatCube testbed is designed to accomplish both of these test objectives using the common framework described in Sections II and III. The two broad types of experiments we have successfully used FloatCube vehicles to run are described below.

A. Flux Pinning Mechanism Investigation

Flux pinning, as noted in Section I, has potential applications as a mechanism for spacecraft assembly and docking, spacecraft reconfiguration, and modular repair. Complex maneuvers involving numerous actuators and modules can be broken down into a series of simple maneuvers involving only a few components, shown mounted on a component payload segment in Figure 8. Each of these maneuvers can be verified individually before being performed in sequence to achieve the desired final configuration of modules. When each step of the routine has been verified, the FloatCube testbed can mount each component module simultaneously to perform the full reconfiguration routine.

The most basic flux pinning tests involve magnets and electromagnets mounted on one FloatCube pinned to a superconductor on another vehicle. The magnets act as actuators for the multivehicle system, moving the vehicles by changing the magnetic field strength or direction in the FPI. Additional interfaces can be mounted by adding more magnets and superconductors to these two vehicles and by introducing additional vehicles to the test surface.

One of the mechanisms currently under investigation is a close range docking maneuver driven by a flux pinning interaction. The desired result is an arrangement of magnets, magnetic material and superconductors such that a second vehicle with a magnet array is attracted towards an equilibrium location and orientation specified by a FPI. This maneuver is currently being investigated using the experimental component payload segment configuration (enclosed in half cube shells for equipment protection) of two FloatCube vehicles, one of which is shown in the top of Figure 8.

B. Mission Hardware Verification

After flux pinning mechanism concepts are experimentally validated, the next step of development is their implementation on a vehicle operating in a space-like environment or a flight test in orbit. These self-contained vehicles require rigorous testing to ensure correct operation, since the modification of the vehicle during the mission is difficult if not impossible. The FloatCube system provides an important intermediate step between breadboard component testing and vehicle deployment.

Figure 8. FloatCube vehicle with experimental component payload for sensor validation test (top); FloatCube with CubeSat mock module for hardware verification (bottom).
Fully assembled, mission-ready nanosats can be mounted as a FloatCube vehicle payload, as shown in section III, and interact with one another in 3DOF. This allows verification of flux pinning components, sensors, electronics systems and communications in a laboratory environment. A CubeSat mock module used in previous microgravity testing\(^1\) is shown mounted on a FloatCube for testing in the bottom of Figure 8.

An upcoming microgravity test mission will take advantage of this capability to verify hardware before flight. The ongoing tests involve two mock CubeSats assembled from half cube shells. Following breadboard component tests and module construction, we will use the FloatCubes to perform mission hardware verification and demonstrate the desired docking sequence in the laboratory. This will also allow us to practice the mission maneuvers and correct any potential problems before deploying the hardware in the time-sensitive environment of a microgravity flight.

VI. Conclusion

The FloatCube testbed presented in this paper allows for a wide range of experiment types to support ongoing investigations of flux pinning mechanisms. Multiple ongoing research projects on flux pinning interactions take advantage of the numerous capabilities available through the FloatCube system. By developing a standard testbed which also conforms to mission hardware components, we can more rapidly perform necessary experiments to develop working flux-pinned mechanism.

By using a modular architecture and distinct vehicle segments, the FloatCubes are flexible and can accommodate experiments using hardware the both the breadboard and flight level. Physically independent vehicles with communication capability allow for the construction of multi-module formations and multi-step interaction routines. Having this robust testbed will allow the rapid implementation of new experiments without the need for new supporting hardware that is not directly involved in the flux pinning interactions. Sharing common control components and interface with current flight hardware allows for verification before mission deployment. The FloatCube testbed uses components that are easily available and inexpensive, allowing other research programs to easily implement this design for CubeSat spacecraft testing. Although designed specifically to address the need of the flux pinning research programs, the FloatCube testbed can provide a low-cost, user-friendly 3DOF environment for any nanosatellite-scale vehicle hardware.

References

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