A New Actuator for On-Orbit Inspection

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ABSTRACT

Small satellites can enable a new kind of mission architecture: inspecting larger satellites on orbit in close proximity without mechanical contact. Induction coupling is a new actuation technology that can augment on-orbit servicing by exploiting eddy-current forces and torques. Current technologies for applying forces and torques between two spacecraft share a glaring disadvantage: they require direct contact or propellant. By using the forces between a magnetic field and the electric currents it induces in a target, an induction coupler can control the relative position and orientation between a chaser spacecraft and a target without physical contact. A system utilizing these eddy-current effects places relatively few requirements on the target and chaser compared to other proposed electromagnetic actuation concepts. This paper presents a system overview of a contactless induction coupler, outlines those requirements through the analysis of an inspection mission on the International Space Station, and traces them to flight applications through ongoing experimental work.

INTRODUCTION

An induction coupler uses magnetic eddy currents to create forces between itself and the conductive materials that make up a target. The coupler requires no mechanical contact with a target, nor does it demand cooperation from the target. The coupler can also operate on electricity alone, rather than requiring propellant. Because most satellites include conductive material in their structure—notably aluminum honeycomb with aluminum facesheets or aluminum beams—induction couplers may be the closest thing we have to science fiction's tractor beam: a device that can produce contactless forces on an uncooperative target.

Induction couplers show promise for spaceflight applications, offering three major advantages. First, the small forces associated with magnetic fields across meter-scale distances can dominate gravity, friction, aerodynamic drag, and other effects, which are far less pronounced in orbit than in a terrestrial environment. Second, fully deployed spacecraft rarely offer straightforward means for mechanical grappling; so, the ability to interact without the potential for contact damage is valuable. Third, induction couplers offer the ability to maneuver without expendables, eliminating risks associated with propellant-plume impingement and extending the useable lifetime of a spacecraft.

A small spacecraft could use an induction coupler to control its motion relative to a much larger target like the International Space Station (ISS), crawling along the target's surface without ever touching. This on-orbit inspection technique resembles the locomotion and functions of underwater robots that now inspect pipelines and shipwrecks.

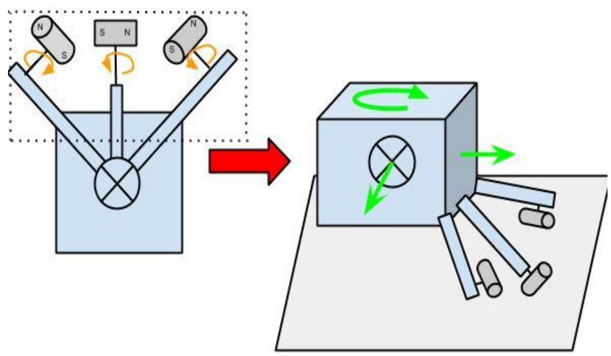


Figure 1: A spacecraft can use an induction coupler with three spinning magnets to create actuation forces and torques

Current interest in on-orbit servicing (OOS)[1] is a strong motivation for advancing induction coupler technology. One of the fundamental technological use cases is that of a small inspection vehicle whose interactions with the target do not produce significant motion in that target—for example, an ISS inspection vehicle. Such a vehicle is primarily concerned with regulating planar motion along the surface of the target and stabilization of out-of-plane translation. This paper describes a study of how the planar component of that motion can be achieved with induction couplers.

BACKGROUND

Other Technologies

There are other technologies that can produce contactless forces between a spacecraft and a target. Coulomb forces have been shown to produce useful interactions between two charged spacecraft as long as the distance between them is less than a Debye length. [2] A number of different systems produce contactless forces with magnetic interactions among controlled dipoles on both the spacecraft and the target. **Error! Reference source not found.** All such approaches place requirements for specific hardware on both the chaser and the target (that is, the target must have launched with certain features already in place.) However, no spacecraft currently in orbit meet these criteria, to the authors' knowledge.

Laser tweezers can produce contactless forces on an uncooperative target. **Error! Reference source not found.** However, the tweezers are best at manipulating micron-scale particles, a size restriction that no spacecraft beyond about TRL 16 can meet.[6] Thruster plumes can also produce forces between a spacecraft and a target. However, typically the combustion products from thrusters carry significant risk of contaminating optical instruments and solar panels, among other disadvantages. We conclude that current technology is limited to direct mechanical contact as the only other option to create forces on a target that has not been designed for an interactive mission.

Induced-Current Forces

An induction coupler generates an eddy-current force that acts between itself and a target. Eddy-current forces start with a time-varying magnetic field. The field induces an electrical eddy current in a conductive target. In turn, that induced current interacts with the magnetic field and produces force between the conductive target and the source of the magnetic field.

In broad strokes, the generation of eddy-current forces is a straightforward manifestation of Maxwell's equations.[5]

1. Any material with finite conductivity experiences a voltage gradient in response to a time-varying magnetic field.

2. The voltage difference drives a current through the material. This current flows in a direction to cancel the change in the magnetic field with a time delay.

3. This induced current acts like the familiar example of a wire in a magnetic field, and experiences a force.

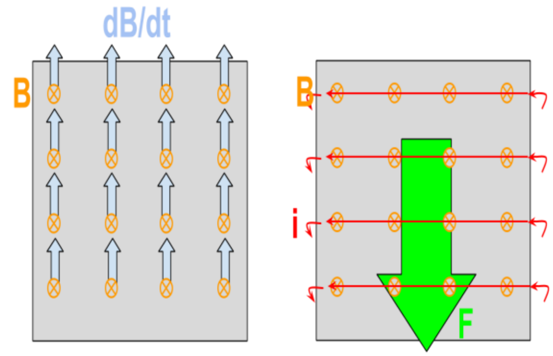


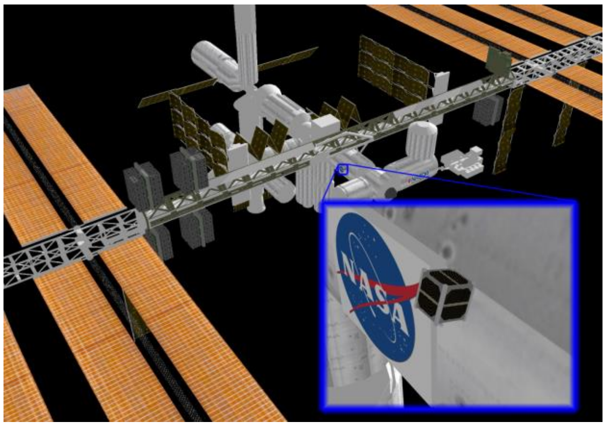
Figure 2: A magnetic field directed into the conductor changes in the upwards direction. This change induces current loops that interact with the original B field to create a downwards force.

These steps give intuition for the physical process, but they are a gross oversimplification. More generally, the currents in the conductor depend on the geometry of the material, material properties, the direction and magnitude of the changes in the magnets in the induction coupler, and the velocity of the target relative to the induction coupler. In fact, the force depends not just on the current, but also on the magnetic field's magnitude and direction. Compounding the subtlety is the unavoidable coupling between the magnetic field and the kinematics of the magnets in the induction coupler. These interdependencies make the force sensitive to the state of the system. Induction couplers exhibit many nonlinearities, which demand a rigorous and informed approach to implementing the technology.

Induction couplers can produce force in any direction relative to the target, for example both tangential and perpendicular to a surface on that target. Therefore, a small spacecraft generating a time-varying magnetic field could produce forces in all three translational degrees of freedom. Extending that idea, two induction couplers separated by a moment arm could also produce torques to orient the spacecraft.

There are two ways for an induction coupler to generate its changing magnetic fields and resultant forces. While both moving permanent magnets and variable electromagnets can generate those forces, each kind of magnet is especially good at producing different sorts of force. A single electromagnet with a sinusoidal driving current can always produce a repulsive force between itself and the target. Replicating that force with a permanent magnet would require either a closed-loop linear actuator or a complicated set of linkages. Similarly, a simple permanent magnet mounted on a motor shaft easily produces horizontal shear forces between itself and the target, a force that is hard to replicate with electromagnets. It isn't yet clear which combination of permanent and electromagnets optimally generates 6-degree-of-freedom (DoF) forces. There may not be an optimal configuration. Instead, the composition of the magnets in an induction coupler may depend on the mission profile - different for an inspection vehicle operating near the surface of a large target than a free-flier maneuvering near a smaller target. This paper focuses primarily on the former.

MISSION DESCRIPTION



A small inspection spacecraft can use induction couplers to crawl along the surface of a larger target spacecraft without physically grappling the target. The inspector can fulfill a number of functions including investigating problematic areas, scanning for damage, performing small tasks, or providing support for astronauts on space walks. This paper focuses on the International Space Station (ISS), but a similar inspection spacecraft could enable unique OOS missions to inspect and repair other large satellites.

The inspection spacecraft would use induction couplers to pull itself along the aluminum surface of the ISS, maintaining a separation distance of a few centimeters. From this vantage point, it could act like a damage-inspection Roomba, canvassing the surface and automatically detecting damage from micrometeorite strikes. It could also be controlled directly by an astronaut in the space station to look at a problem area and possibly use an attached robotic arm to perform small actions. During spacewalks, the spacecraft could act like an extra pair of hands, remaining near an astronaut and holding tools. Robotnaut and the Canada Arm have demonstrated the value of this role, but are limited by rails to specific locations.

The ability to traverse the exterior of the ISS without being constrained to travel on rails, attach to specific hard points, or manage a finite propellant supply can free up one of the most valuable resources on the ISS - astronaut time.

INDUCTION COUPLER BEHAVIORS

For simplicity this discussion considers induction couplers comprised of magnets—whether permanent magnets or electromagnets—that can be characterized as single magnetic dipoles. Of particular interest here are induction couplers that include permanent magnets. Spinning permanent-magnet induction couplers consist of a mechanism with one or more permanent magnets spinning with variable speed about axes perpendicular to their dipole moments. The orthogonality of the dipole moment and the spin axis maximizes the change in magnetic field and therefore helps maximize the eddy-current effects. In its most elementary form, there is only a single dipole that spins in a plane. However, each spinning mechanism within the induction coupler can include any number of magnets. A motor spins this circumferential collection (or “array”) of magnets.

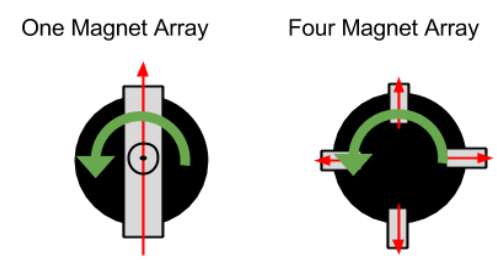


Figure 3: Magnet arrays with one dipole (left) and four dipoles (right)

The more magnets in an array, the more uniform the magnetic becomes, smoothing the spatial variation around the exterior of the array. This smoothness decreases the change in the magnetic field as the magnets spin, which may be undesirable in an application that requires high eddy-current force. The number of magnets per array is one of the many considerations in the design of an induction coupler.

A straightforward example of an induction-coupler system is a single array spinning about an axis perpendicular to a flat, conductive surface. In this example, the coupler produces a force perpendicular to ω cross **d** where w is the angular velocity vector of the array relative to a plate-fixed reference frame, and **d** is the distance from the center of the dipole field to the surface.

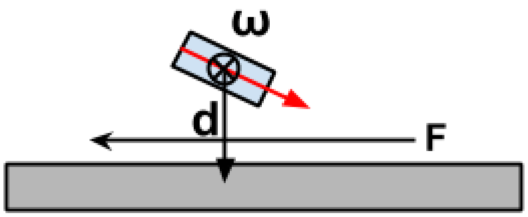


Figure 4: A dipole spinning clockwise with angular velocity (ω) at distance d above a target that extends out of the page generates a force (F) directed to the left.

Each array is associated with a single control degree of freedom. Its force and torque may project onto any of the six rigid-body degrees of freedom, depending geometries: the orientation of the coupler relative to the spacecraft's center of mass, distance to the surface and the topography of the surface. . To first order, for a flat plate and a spin axis in a plane perpendicular to the surface normal, the effect is a force only, with no significant moment. The chaser spacecraft can use this force to torque the spacecraft if it is located so there is a moment arm between the spacecraft's center of mass and the array. Alternatively, two couplers can create a moment through a couple, which would be independent of the couplers' position relative to the target's mass center.

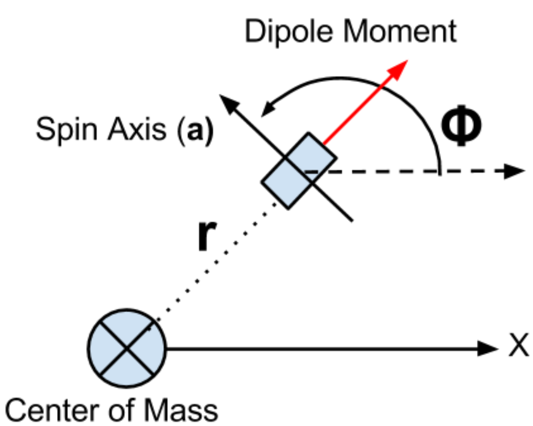


Figure 5: A single-magnet induction coupler.

Experimental development of an induction coupler has shown that these forces vary with the magnitude and sign of **ω** and can produce milliNewton shear forces perpendicular to a surface for low power, using small COTS motors and permanent magnets. Specifically, two small motors driven by 12V at a 25% duty cycle while holding two neodymium permanent magnets (with an approximate dipole moment calculated to be around 8.5 $*10^4$ Am^2) have together generated 5 mN, or 2.5 mN apiece. Spinning at 4200 RPM, each motor drew 0.25 amps of current, dissipating 0.75 Watts of electrical power. This power consumption corresponds to a power-specific force of 3.33 mN/Watt.

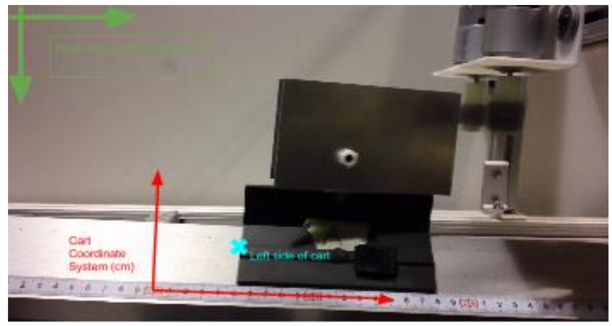


Figure 6: An aluminum target on a low-friction air track (left) is moved by two spinning magnets (upper right.)

The angular velocity of the array determines the force because the induced voltage scales with ||**v** x **B**|| where **v** = **ω** x **d** is the relative velocity between the target conductor and the magnetic field. **d** is the vector position of the target relative to a point on the array's spin axis.

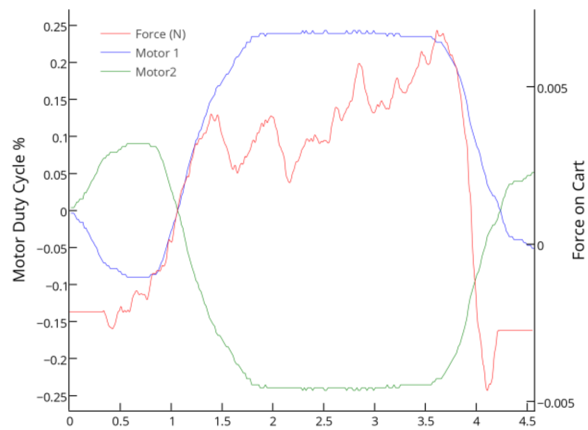


Figure 7: Force on a one-dimensional air-track levitated cart vs. motor speed for a small, two-motor induction coupler. Oscillations in the force reported here are due to a combination of sensor artifacts and the dynamics of the cart.

The direct scaling between force and **ω** makes two assumptions: that 1/**ω** is much larger than the characteristic time of the LR circuit that the conductor approximates and that the kinematics of the chaser and target are much slower than the period of rotation of the spinning magnetic fields that act on the target.

The force magnitude decreases approximately with $1/d^4$. Larger magnets increase the force (linearly with magnetic-moment magnitude). Greater thickness and conductivity of the target increase the induced current and thereby scale up the force.[5] Spin speed tends to increase the force linearly by increasing the rate of change in the magnetic field, but increasing speed past a certain point shows diminishing returns because the so-called skin depth associated with induced current in the material drops with higher frequency. These trends provide the basis for designing an optimal induction coupler for a specific application.

INDUCTION COUPLER SYSTEM

The rotational speed of each array controls the force between that array and the surface of the target. The sum of the forces from all the arrays and their resultant torques can be mapped through the linearized dynamics of the target and chaser to plan control inputs based on a desired maneuver. Nonlinearities are likely best accommodated through gain scheduling, a topic that the authors intend to take up as future work.

The present analysis assumes that the inspection spacecraft maintains a small constant distance from the surface. With an operating range of a few centimeters, the surface for most of the ISS looks like an infinite plane to the inspection spacecraft. The analysis assumes that the proposed inspection vehicle conforms to the cubesat standard so the mass of the entire system is not above m = 4 kg.

An induction coupler with only one or two spinning arrays can achieve planar motion. The motion is nonholonomic; i.e. the chaser's ability to move in a given direction depends on its orientation.

Three spinning arrays can drive three independent planar degrees of freedom. In practice, more should be used for redundancy and greater control authority. As long as the arrays have sufficient spatial separation, their forces simply superimpose. For a particular application, these principles inform tradeoffs among force, power, mass, and the reliability of moving parts introduced by the additional arrays.

In the induction coupler, each array is the located at some radius, $\boldsymbol{r}$, from the spacecraft's center of mass. Each array has a spin axis $\hat{\mathbf{a}}$ oriented parallel to the target surface at an angle φ from the x-axis in spacecraft coordinates. See Figure 5: A single-magnet induction coupler.

For N arrays in this special orientation, the transformation between the angular speeds of the arrays and the net force and torque on the spacecraft is:

$$\begin{bmatrix} F_x \\ F_y \\ \tau \end{bmatrix} = C \begin{bmatrix} \cos(\phi_1 - \pi/2) & \cos(\phi_2 - \pi/2) & \dots & \cos(\phi_N - \pi/2) \\ \sin(\phi_1 - \pi/2) & \sin(\phi_2 - \pi/2) & \dots & \sin(\phi_N - \pi/2) \\ \boldsymbol{r}_1 \cdot \hat{\boldsymbol{a}}_1 & \boldsymbol{r}_2 \cdot \hat{\boldsymbol{a}}_2 & \dots & \boldsymbol{r}_N \cdot \hat{\boldsymbol{a}}_N \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \dots \\ \omega_N \end{bmatrix}$$

(1)

In (1) C is a matrix of constants that take the angular velocities to forces and torques. These constants will vary with the distance to the target and the target's properties.

The Jacobian J is the geometry-dependent matrix from (1):

$$J = \begin{bmatrix} \cos(\phi_1 - \pi/2) & \cos(\phi_2 - \pi/2) & \dots & \cos(\phi_N - \pi/2) \\ \sin(\phi_1 - \pi/2) & \sin(\phi_2 - \pi/2) & \dots & \sin(\phi_N - \pi/2) \\ \boldsymbol{r}_1 \cdot \hat{\boldsymbol{a}}_1 & \boldsymbol{r}_2 \cdot \hat{\boldsymbol{a}}_2 & \dots & \boldsymbol{r}_N \cdot \hat{\boldsymbol{a}}_N \end{bmatrix}$$

(2)

The speed-force Jacobian (2) imposes constraints on the design of the induction coupler.

* $\mathbf{r}_i \cdot \hat{\mathbf{a}}_i$ must be nonzero for at least one array, corresponding to the requirement that all of the spin axes cannot be perpendicular to their moment arms, nor can all r_i be zero (i.e. some of the arrays cannot be at the unlikely location of the target spacecraft's center of mass).

* Not all of the spin axes $\boldsymbol{a}_i$ can be parallel. If they are, all φ_i to be integer multiples of π radians apart, and the Jacobian would not be full rank.

The specific case of an inspection vehicle equipped with an induction coupler consisting of three magnet arrays with $\|\mathbf{r}\|$= 10 cm helps fix ideas.

$$\phi = \begin{bmatrix} \frac{3\pi}{4} & \frac{pi}{2} & \frac{pi}{4} \end{bmatrix} \quad (3)$$

and

$$\hat{\boldsymbol{r}} = \begin{bmatrix} \frac{\sqrt{2}}{2} & 0 & -\frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & 1 & \frac{\sqrt{2}}{2} \end{bmatrix} \quad (4)$$

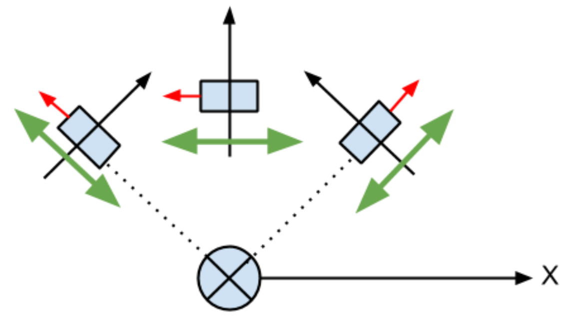


Figure 8: Example induction coupler architecture with three single-magnet arrays.

The Jacobian is

$$J = \begin{bmatrix} \frac{\sqrt{2}}{2} & 1 & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} & 0 & -\frac{\sqrt{2}}{2} \\ 0 & 1 & 0 \end{bmatrix} \quad (5)$$

This Jacobian ignores the constants scaling F_x, F_y, and τ based on the system state and physical constants of the target.

An induction coupler of this type on a 4 kg spherical spacecraft of radius 0.1m, can generate a linear acceleration of about 2×10^{-3} m/s^2 and an angular acceleration of 9×10^{-3} rad/s^2. These values, while modest, allow an inspection vehicle to overcome perturbation forces and move slowly over the surface of the ISS to inspect it. These values are based on a small prototype comprised of COTS components and an induction coupler with only three magnet arrays. Using additional arrays and optimizing the hardware are two straightforward ways to increase the capabilities in this example.

CONCLUSION

This paper presents a starting point for induction coupler technology. It describes the physics of spinning magnet arrays producing contactless forces and torques on any conductive target. Preliminary experiments verified and measured these forces. When coupled together, three or more arrays can produce three independent degrees of freedom in the plane above the target's surface.

Induction couplers offer the prospect of inter-body forces that enable close-proximity inspection of a large target vehicle by a smaller chaser spacecraft, all without mechanical contact. There are many paths for future induction coupler research that extend this key conclusion. The frequency response of the system and its sensitivity to system state and environment are important to future designs. This analysis considers only planar motion. However, remaining in that plane requires an actuator associated with that degree of freedom, and ideally the chaser spacecraft or inspection vehicle would exhibit full six-degree-of-freedom maneuverability.

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