

## Todo list

Terms to associate with technical meaning:	
Traversal surface	
repel	
attract	
planar force	
planar torque	
coordinate system	1
cite papers on difficulty of OOS	1
cite paper about uses of OOS	2
Is it worthwhile to mention the DARPA Phoenix project?	2
cite different systems.	2
physics book citation	2
Figure: picture of array models	2

## 1 Abstract

Can you move along a surface in space without propellant or physical contact? On-orbit servicing requires a robot to operate in close proximity to the surface of a target spacecraft in order to inspect, refuel, or repair it. Robotic operation at such small distances is difficult in space because spacecraft are fragile and often have poorly known dynamics that are never damped out by the environment. Current actuators for locomotion and grasping during on-orbit servicing require physical contact with the target, propellant, or cooperation from the target. This paper presents an new actuator - the induction coupler - that generates eddy-current forces between a robotic orbital inspector and the conductive exterior of its target. These forces allow the inspector to crawl along the surface of a target while maintaining a safety gap. Sets of induction couplers can exert control forces and torques in all six rigid-body degrees of freedom by strategically repelling and shearing across the surface of the target. Spinning arrays of permanent magnets produce shearing eddy-current forces and current-oscillating electromagnets produce pushing eddy-current forces. The induction coupler's ability to generate forces is state dependent: its forces and torques depend both on the relative orientation of the coupler to the surface and the surface's geometry. This paper uses an analytical model of eddy-current forces to simulate the set of manoeuvres necessary to generate the control forces and torques that can move and orient a robotic orbital inspector. Experiments on a low-friction test bed demonstrate a successful implementation of the actuator and verify the manoeuvres.

## 2 Introduction

On-orbit servicing (OOS) is a valuable but difficult robotic task. [] Just as

Terms to associate with technical meaning:  
Traversal surface  
repel  
attract  
planar force  
planar torque  
coordinate system

cite papers on difficulty of OOS

on earth, large assets like the International Space Station (ISS) or geostationary satellites experience wear and unexpected problems that require inspection, repair, or refuelling. These tasks are well suited for robots because it is less dangerous and expensive to send an inspection vehicle to geostationary orbit or outside the ISS than a human spacewalker. Manoeuvring close to a target is essential to OOS and is a particularly risky proposition on orbit. There are presently three methods for an inspector to manoeuvre close to the surface of its target: it can physically grapple the surface to pull itself along; it can use propellant and thrusters; or it can use cooperative, non-contacting electromagnetic systems installed both on the inspector and the target. Grappling has many potential risks in an uncertain, low-friction environment. Propellant is expensive and can damage sensitive targets. Cooperation is infeasible in many situations because most spacecraft did not launch with the necessary subsystems: spacecraft are not designed to be inspected or repaired by robots. However, the ISS and most spacecraft composed of aluminium plates, curves, and beams. By introducing a changing magnetic field, a robotic inspector can induce eddy currents in these non-magnetic but conductive components and use the reaction force between the field and the currents for actuation. These eddy-current forces have several terrestrial applications from trash separation [1] to mag-lev propulsion, [2] but have never been used in either a robotics or orbital context. An eddy-current based actuator called an induction coupler, can provide a completely new way to perform robotic locomotion and manipulation in space. The first step towards an induction coupler locomotion system is to show how to produce actuation in each degree of freedom (DoF). What is it capable of given different states? Eddy-current forces depend both on the robot's pose and the geometry of the environment. Simulating general eddy-current forces is normally done with finite element analyses (FEA) [3]. FEA are unsuitable for dynamically modelling induction couplers for two reasons: they are both too slow to run at each time step and their mesh of nodes needs change with the geometry of the system. Paudel and Bird derived an extensible analytical solution for eddy-current forces near a flat plate that enables fast simulations of induction couplers.[4] Section 3 derives the Jacobian matrices that map between the inputs to an induction coupler and the resultant forces. Section 4 describes and simulates the necessary manoeuvres to move in each dof. Finally, Section 5 presents experimental verification of each manoeuvre with a prototype induction coupler system on a low-friction testbed.

cite paper about uses of OOS

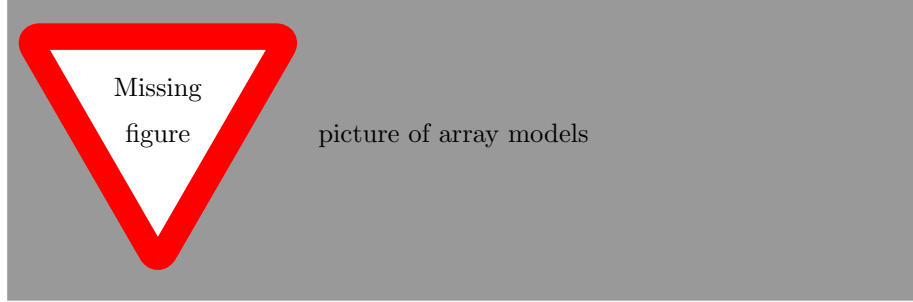
Is it worthwhile to mention the DARPA Phoenix project?

cite different systems.

physics book citation

### 3 Physics Model

Using the results of [3], the force from a single rotating array of permanent magnets can be approximated as



$$\mathbf{F}_{PM} = A(g) (\mathbf{a} \times \mathbf{n}) \omega \quad (1)$$

Where  $A(g)$  is a function of the gap between the array and the conductive surface,  $\mathbf{a}$  is the spin axis of the array,  $\mathbf{n}$  is surface normal vector and  $\omega$  is the angular velocity of the array. Similarly, the force from a single current-oscillating electromagnet is

$$\mathbf{F}_{EM} = B(g) \mathbf{n} i \quad (2)$$

Where  $B(g)$  is a function of the gap between the array and the conductive surface and  $i$  is the RMS current through the electromagnet. The upshot of this model is that a mechanically rotating array of permanent magnets will generate a force force approximately perpendicular to the surface.

### 3.1 Permanent Magnets

### 3.2 Electromagnets

## 4 Movement Flavors

### 4.1 Planar Rotation

### 4.2 Planar Translation

### 4.3 Perpendicular Translation

### 4.4 Perpendicular Rotation

## 5 Experimental Verification

## 6 Conclusion

A robotic on-orbit service vehicle can use induction couplers can produce locomotive forces in all six rigid body degrees of freedom near a conductive surface. Rotating permanent-magnet arrays generate forces perpendicular to both their axes of rotation and the conductive surface. Current-oscillating electromagnets generate forces directly away from the surface. A pair of rotating arrays can produce  $\hat{x}$  and  $\hat{y}$  forces in the plane of the traversal surface. These two arrays can

also produce torques in the  $\hat{z}$  direction. This pair of arrays can take advantage of the surface geometry to generate forces in the  $\hat{z}$  direction by generating shear forces along a non-flat surface whose  $\hat{x}$  and  $\hat{y}$  components cancel but whose  $\hat{z}$  components add. A single electromagnet generates force in the  $+\hat{z}$  direction. The force from the electromagnet can also generate torques based on its relative location to the system's center of mass. These maneuvers are demonstrated in simulations and verified on a low-friction testbed.

Future work will focus on two areas - adaptive controllers and movement planning. A robotic inspector will need adaptive controllers to account for induction coupler's strong dependence on poorly known parameters of the environment. The inspector will also need to plan movements carefully because its ability to exert control with an induction coupler is based on both its state, the local geometry.