Utilizing Deep Reinforcement Learning to Effect Autonomous Orbit Transfers and Intercepts via Electromagnetic Propulsion

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Problem

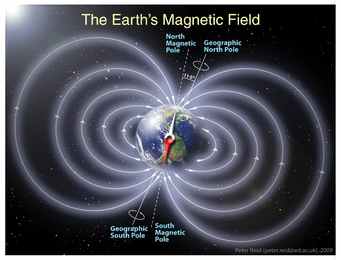
The growth in space-capable entities has caused a rapid rise in the number of derelict satellites and space debris in orbit around Earth, which pose a significant navigation hazard.

Objectives

Develop a system that is capable of autonomously neutralizing multiple pieces of space debris in various orbits.

Background

- Dangerous amounts of space debris in orbit, estimates vary
  - 20,000+ tracked objects larger than 10 cm diameter
  - Est 500,000 objects larger than 1 cm in diameter
  - Est 100 million objects smaller than 1cm in diameter
- Orbital speeds of these objects vary from 100+ kph to 28,100 kph
- Spacecraft collisions due to space debris have been sparse so far
  - 1985 – US Anti-satellite missile destroys aging weather satellite. Decayed orbit resulted in minimal additional debris
  - 1996 - French satellite damaged by debris from French rocket launched in 1980's
  - 2007 - China destroyed a old weather satellite via a missile
    - Added 3,000+ trackable debris to orbit
  - 2009 - derelict Russian satellite collided with and destroyed Iridium communication satellite
    - Added 2,000+ trackable debris to orbit
- Kessler Syndrome remains an increased possibility
  - Cascade of debris collisions in orbit creating more debris in chaotic orbits
  - Would lead to many orbits becoming inaccessible due to debris danger
- The Earth has a geomagnetic field surrounding it
  - Extends more than 600,000km above the surface
  - Produced by currents in Earth's core
  - Interactions between Solar storms and the Geomagnetic field cause it to expand or Shrink

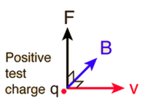


Cross-section of Geomagnetic field. (NASA)

- Lorentz Force

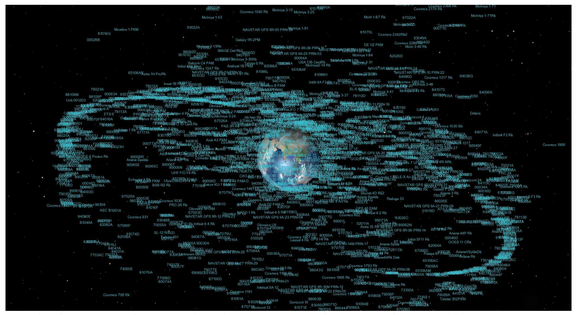
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

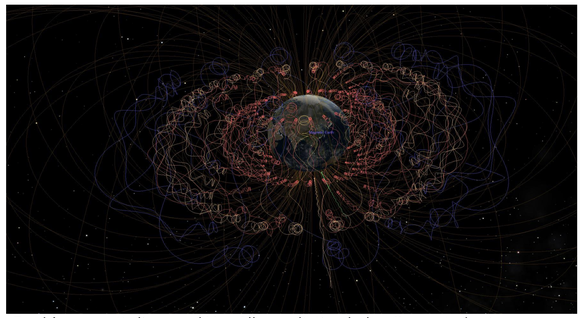
Electric force *Magnetic force*

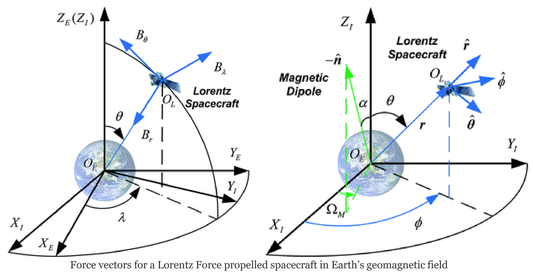


- Lorentz equation describes the force exerted on a charged particle *B* by electrical field *E* and magnetic field *v*
- In materials, particles also generate forces described in Lorentz equation
  - Systems of equations involving conductive properties, specific heat, insolation, and density of a material must be solved to accurately predict magnetic forces exerted on it
- Electro-dynamic tethers exploit changes in earth's magnetic field across different orbital areas to generate electricity
- Neural Networks have been shown to be effective for continuous low-thrust orbit changes, and resilient to missed thrust events

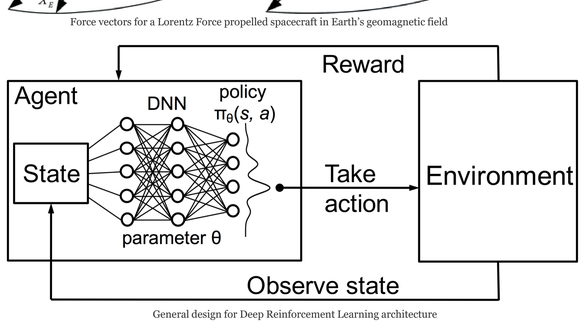
Software & Simulations


Tracked spacecraft in Earth orbit. Generated using Celestia Software.

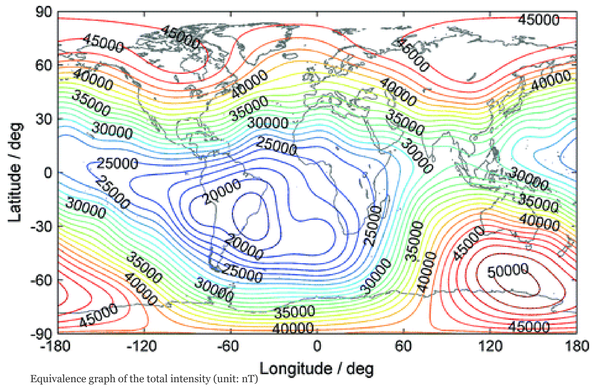

Earth's magnetic lines and Van Allen radiation belts. Generated using Celestia Software.



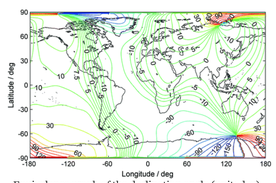
Force vectors for a Lorentz Force propelled spacecraft in Earth's geomagnetic field

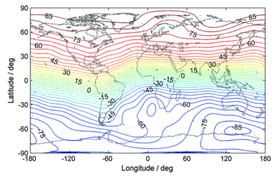


General design for Deep Reinforcement Learning architecture

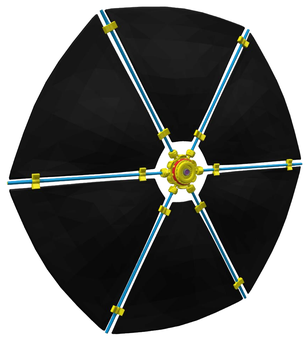


Equivalence graph of the total intensity (unit: nT)


Equivalence graph of the declination angle (unit: deg)


Equivalence graph of the inclination angle (unit: deg)

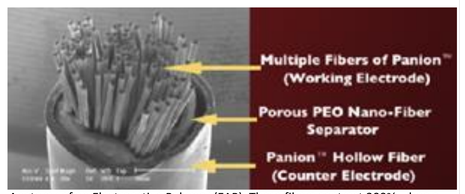
Spacecraft Design


Rendering of current debris capture spacecraft design.

- Lifetime >6 months
- Orbit: 2,000km – 36,000km

Onboard capabilities:
- Real-time Operating System
- Autonomous target selection filter
  - Capable of ignoring active spacecraft
- Carbon-fiber composite net sections
- Net deployment and actuation system
  - Powered by Electroactive polymers (EAPs)
- Telemetry uplink/downlink

Key Capabilities
- Low-power onboard Neural Network for propulsion system control and target selection
- Radiation-resistant software



Anatomy of an Electroactive Polymer (EAP). These fibers contract 300% when a current is run through them at high voltage. Photo courtesy of Jet Propulsion Lab.

Results

- **Analysis**
- The data suggests spacecraft highly capable of neutralizing/capturing small to intermediate debris
- In simulations, spacecraft was able to capture and/or neutralize debris ranging in mass from 1g to 100g
  - Satellites suffered damage in some simulations
  - Simulations show that damaged segments of satellite were vaporized, which means that no additional debris was added to orbit
- Neural Network based on Deep Deterministic Policy Gradient (DDPG) effective at low-thrust orbit transfers in 2D Hohmann transfer problem
- Using ASTOS simulation software, mission-representative model of spacecraft and experimental propulsion system
  - Interfaced with DRL to train the Neural Network with realistic data
- **Future Studies**
- Train DDPG for 3 dimensional orbit transfer problems
- Incorporate European Space Agency's Space Debris Software Suite
  - Collision and intercept probability analysis with DRAMA software
  - Train Neural Network for safe deorbit of debris using Oriundo model
- Manufacture CubeSat prototype
  - Multi-electrodynamic tether
  - Onboard AI via next-gen VPU

Applications

- **Deep Reinforcement Learning for Orbit Transfer**
  - Useful for effecting intercepts between primary spacecraft and target orbit
  - Highly efficient for low-thrust maneuvers
- **Magnetic propulsion system**
  - Propellant-less propulsion system could be used in future spacecraft design for long mission life
  - Provides potential for satellite constellations in close formation
  - Could be used for planetary orbit insertion for deep space missions

Conclusions

Results indicate a system similar in design to that of spacecraft outlined in this study has the potential to drastically reduce amount of space debris and derelicts in Earth orbit, thus reducing the risk of a Kessler syndrome scenario happening.

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