Acta Astronautica 222 (2024) 81–86

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Research paper

De-orbiting space debris via interaction between a permanent magnet and Earth's magnetic field: A feasibility study

Devin K. Dalton [a,b,*], Jake J. Abbott [a,b], Henry C. Fu [a]

[a] Department of Mechanical Engineering, University of Utah, 1495 E. 100 S., Salt Lake City, 84112, UT, USA
[b] Robotics Center, University of Utah, 1495 E. 100 S., Salt Lake City, 84112, UT, USA

ARTICLE INFO

Keywords:
Orbital debris
Space junk
Remediation
Active removal

ABSTRACT

The accumulation of space debris is an ever-increasing problem. Systems that can reliably de-orbit (i.e., decrease the time to re-entry for) an inactive resident space object (RSO) are highly sought after. In this paper, we investigate the feasibility of utilizing the forces owing to the interaction of Earth's magnetic field with a permanent magnet that has been attached to an RSO in low Earth orbit. We consider an actively controlled permanent magnet that is optimally oriented to remove energy from the system, and the most favorable magnet-to-RSO mass ratio. We show that, even under these best-case assumptions, the interaction between a permanent magnet and Earth's magnetic field is not a viable means of de-orbiting an RSO.

1. Introduction

With the increased availability of, and dependence on, space assets worldwide, the accumulation of space debris is an ever-increasing problem. As of January 1, 2023, 6718 active satellites are currently orbiting the Earth [1]. In August 2022, the European Space Agency reported that 31,870 pieces of space debris were being tracked by space surveillance networks. These networks are only able to track objects larger than 10 cm at low Earth orbit (LEO), and 1 m at geostationary orbit [2]. Statistical models currently estimate another 131 million pieces of space debris that are not being tracked [3]; these pieces are mostly smaller than 1 cm, but still pose a threat to current and future spacecraft. With the dramatic increase of accumulated space debris over time, along with the increasing demand for additional spacecraft, the risk of collision between spacecraft and debris is reaching unacceptable levels and innovative solutions are required.

In addition to existing space debris, The federal communications commission has recently mandated that all satellites placed in LEO (200–2000 km) de-orbit within 5 years of the satellite's end of life [4]. Satellites placed near the International Space Station (400 km) will de-orbit within this time frame naturally [5]. However, satellites placed within the 600–2000 km altitude range will need some sort of onboard de-orbiting system. Any active system, such as a chemical-burning engine, increase both the weight and complexity of the spacecraft and are susceptible to failure. A passive system that can decrease the time to re-entry for an inactive satellite is highly sought after.

It is a well-known fact that Earth has its own magnetic field, and a permanent magnet experiences torques due to this field (e.g., a compass). It is also the case that the permanent magnet experiences forces as well. In this paper, we investigate the potential of utilizing such interactions for the purpose of de-orbiting a resident space object (RSO) such as an inactive satellite or other piece of space debris. The forces generated by Earth's magnetic field are relatively weak, particularly at higher altitudes, but even weak forces may have a substantial effect on the energy of a system if applied over long periods of time (or, more precisely, through long distances). Although a variety of methods for de-orbiting objects have been proposed [6], the interaction of a permanent magnet with Earth's magnetic field has not been investigated previously in the literature.

A completely passive system (e.g., a spherical magnet in a ball-and-socket joint) that could be attached to an RSO would be ideal in terms of simplicity and robustness. When two magnetic dipoles interact, torques are induced that attempt to align one dipole (i.e., the permanent magnet) with the local field created by the other dipole (i.e., Earth). If the RSO does align with the Earth's magnetic field, the resulting force always has a substantial attractive component. This force would tend to pull down on the RSO, which may at first seem to be desirable for de-orbiting. However, in the case of an orbiting RSO, this force would be largely perpendicular to the direction of motion and therefore would not directly alter the total mechanical energy of the RSO. The result would simply be the RSO entering a new orbit that has a slightly lower altitude and higher speed, but not decaying appreciably.

* Corresponding author at: Department of Mechanical Engineering, University of Utah, 1495 E. 100 S., Salt Lake City, 84112, UT, USA.
E-mail address: devinbrasil@gmail.com (D.K. Dalton).

https://doi.org/10.1016/j.actaastro.2024.05.027
Received 23 October 2023; Received in revised form 23 April 2024; Accepted 20 May 2024
Available online 22 May 2024
0094-5765/Published by Elsevier Ltd on behalf of IAA.

A permanent magnet whose orientation is actively controlled (e.g., using a robotic gimbal) could be oriented such that the magnetic force tends to reduce the total mechanical energy of the RSO. Although not completely passive, such a system could utilize solar energy, with no consumables. We can consider an optimal control policy in which the orientation of the permanent magnet is always oriented such that it maximizes the instantaneous energy loss of the system; this represents a realistically achievable best-case scenario.

In a practical implementation for de-orbiting, the total mass of the system would be the combined mass of the RSO and the attached permanent magnet and its control hardware. However, the magnetic forces are only generated by the permanent magnet, with the mass of the RSO contributing only as momentum that must be slowed down. We can consider the limiting case of a zero-mass RSO (i.e., the magnet mass is the total mass) to quantify the upper limit of what we could hope to expect from our proposed form of de-orbiting.

In this paper, we will show that, even in the limiting case of these best-case assumptions, interaction between a permanent magnet and Earth's magnetic field is not a viable means of de-orbiting an RSO for any practical usefulness.

2. Theory

Any orbit can be described by five orbital parameters: semi-major axis (a), eccentricity (e), inclination (i), argument of perigee (ω), and right ascension of the ascending node (Ω). A sixth orbital parameter, true anomaly (ν), defines the position of a satellite within its orbit. The semi-major axis is half the major diameter of the orbital ellipse. Eccentricity specifies the relative shape of the ellipse ($e = 0$ for a circular orbit). Inclination is the angle between the equatorial plane and the orbital plane measured at the ascending node (the point where the orbit passes the equator while traveling north). With the simplifying assumptions we make, the argument of perigee and right ascension of the ascending node will have no effect on our proposed de-orbiting method.

Most space debris is located in LEO [7]. Objects in orbital altitudes around 500 km will de-orbit within 5 years without any assistance [5]. Because the strength of the Earth's magnetic field decays with increasing altitude, we will limit the regime of studied orbits from 600–1000 km in this feasibility study. For simplicity, we will constrain the initial orbit of the RSO to a circular orbit, i.e., $e = 0$ and radius $r_E + 600\,\text{km} < a < r_E + 1000\,\text{km}$, where $r_E = 6378.137$ km is the average radius of Earth. For the purposes of this feasibility study we will assume that the geographic and magnetic poles align, although they in fact differ by approximately $11.5°$ [8].

We will exclusively consider a polar orbit that passes over Earth's magnetic poles, as this represents the best-case scenario for our proposed de-orbiting method. In an orbit around the magnetic equator, it is not possible to create any magnetic force antiparallel to the velocity vector, which, we show below, is critical to assist with de-orbiting. Our proposed method therefore has no effect for an RSO in a magnetic equatorial orbit, and a polar orbit is farthest from this worst-case orbit. We will therefore limit inclination to 90° as best case for the effect of initial inclination for our feasibility study.

Earth's magnetic field can be closely approximated as a magnetic dipole field originating at the center of Earth [8]. The magnetic field $\boldsymbol{b}$ (units T) at a given position $\boldsymbol{r}$ (units m) can be computed as

$$\boldsymbol{b} = \frac{\mu_0}{4\pi\|\boldsymbol{r}\|^3}(3\hat{\boldsymbol{r}}\hat{\boldsymbol{r}}^T - \mathbb{I}_3)\boldsymbol{m}_E \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} is the permeability of free space, $\hat{\boldsymbol{r}}$ is the unit vector in the direction of $\boldsymbol{r}$, $\mathbb{I}_3$ is a 3 × 3 identity matrix, and $\boldsymbol{m}_E$ (units A m^2) is the magnetic dipole of Earth [9]. The magnetic dipole $\boldsymbol{m}_E$ points from the magnetic north pole to the magnetic south pole. The south pole of this magnetic field is located near the geographic north pole and the north pole of the magnetic field is located near the geographic south pole.

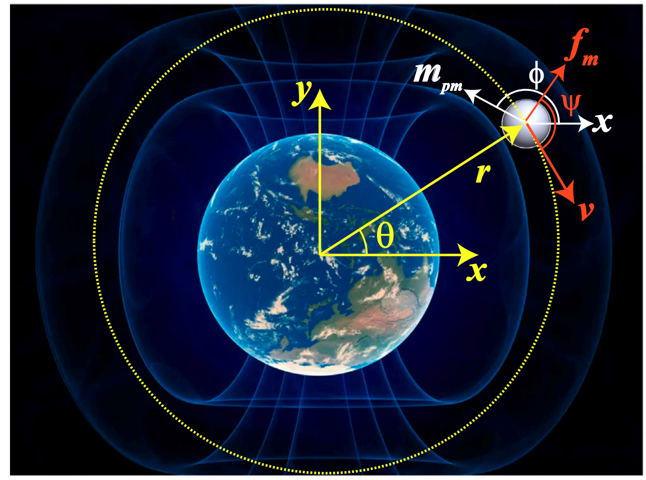


Fig. 1. Definition of variables and coordinate frames. Image of Earth and its magnetic field used under license from Shutterstock.com.

The permanent magnet can also be modeled as a magnetic dipole $\boldsymbol{m}_{pm}$ (units A m^2), where $\|\boldsymbol{m}_{pm}\| = M_{pm}V_{pm}$ is the dipole magnitude, V_{pm} (units m^3) is the volume of the permanent magnet, and M_{pm} (units A m^{-1}) is the average magnetization of the permanent magnet.

The magnetic force $\boldsymbol{f}_m$ (units N) exerted on a permanent magnet within Earth's magnetic field can then be calculated as the interaction between two dipoles [9]:

$$\boldsymbol{f}_m = \frac{3\mu_0}{4\pi\|\boldsymbol{r}\|^4}\Big(\Big(\hat{\boldsymbol{r}}^\top \boldsymbol{m}_{pm}\Big)\boldsymbol{m}_E + \Big(\hat{\boldsymbol{r}}^\top \boldsymbol{m}_E\Big)\boldsymbol{m}_{pm} + \Big(\boldsymbol{m}_E^\top \boldsymbol{m}_{pm} - 5\Big(\hat{\boldsymbol{r}}^\top \boldsymbol{m}_E\Big)\Big(\hat{\boldsymbol{r}}^\top \boldsymbol{m}_{pm}\Big)\Big)\hat{\boldsymbol{r}}\Big) \tag{2}$$

We see that magnetic force decays with distance $\propto \|\boldsymbol{r}\|^{-4}$. This force can be expressed as a linear function of $\boldsymbol{m}_{pm}$:

$$\boldsymbol{f}_m = \mathbb{Q}\boldsymbol{m}_{pm} \tag{3}$$

where $\mathbb{Q}$ is derived in Appendix A.

Because we are exclusively considering a polar orbit that passes over the Earth's radially symmetric magnetic poles, the motion of the orbiting RSO, and the forces and torques on its attached permanent magnet, can be limited to three dimensions as defined in Fig. 1: x, y, and ϕ. The y-axis is parallel with the magnetic dipole of Earth and the x-axis lies in the equatorial plane; θ is measured from the x-axis to the position of the RSO; ϕ is measured from the x-axis to the dipole axis of the permanent magnet. The interaction of the two dipoles produces force $\boldsymbol{f}_m$, and the angle between the RSO's velocity vector and $\boldsymbol{f}_m$ is ψ.

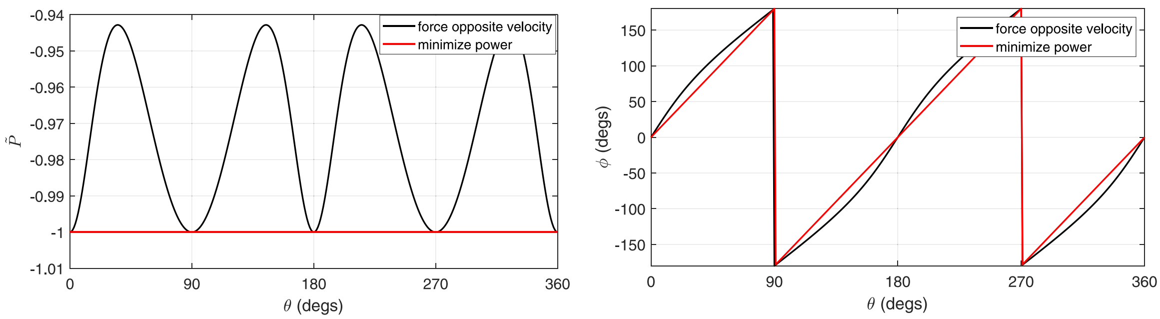
Because we are assuming that the orbiting permanent magnet starts in a circular polar orbit, the initial velocity $\boldsymbol{v}$ (units m s^{-1}) of the RSO depends only on its starting position $\boldsymbol{r}$, which enables us to establish the initial velocity vector as:

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \sqrt{\frac{\mu}{\|\boldsymbol{r}\|}}\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\begin{bmatrix} \hat{r}_x \\ \hat{r}_y \end{bmatrix} \tag{4}$$

where the initial $\hat{\boldsymbol{r}}$ and $\boldsymbol{v}$ have been parameterized by their x and y components, and $\mu = 3.9 \times 10^5$ km^3 s^{-2} is the standard gravitational parameter of Earth.

To determine the orientation (ϕ) that maximizes the energy loss at each point along the orbit, we will use the concepts of work and power. Work is the amount of energy put into the system. Therefore, minimizing (i.e., making the most negative) the time rate of change of work (i.e., power) will maximize (i.e., optimize) the orbital energy loss. The power (units W) put into the system can be expressed as:

$$P = \boldsymbol{f}_m \cdot \boldsymbol{v} = \|\boldsymbol{f}_m\|\|\boldsymbol{v}\|\cos\psi \tag{5}$$



(a) Nondimensional power (b) Permanent-magnet orientation

Fig. 2. (a) The nondimensional power $\tilde{P}$ and (b) associated permanent-magnet orientation ϕ, at each value of θ, for magnetic forces generated using two methods: the force directed opposite to the velocity, and the force that minimizes power. Note that the discontinuity of ϕ is simply representational.

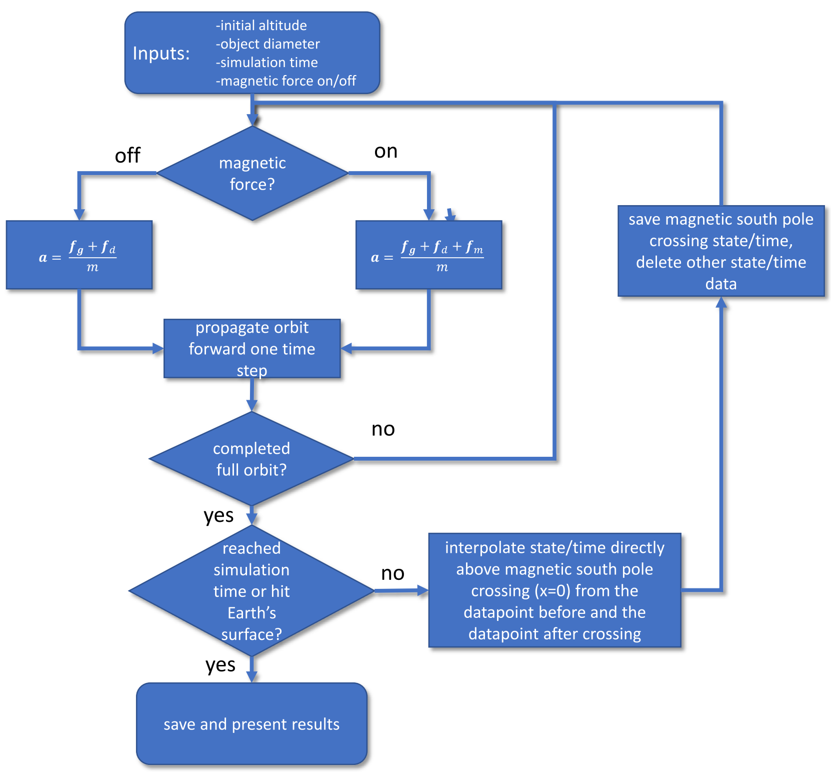


Fig. 3. Pseudo-code showing the simulation structure and logic.

For our assumed circular orbit and Earth's magnetic moment pointing toward the geographic south pole, it can be shown that the power simplifies to:

$$P = -\frac{3\mu_0 \|\boldsymbol{m}_E\| \|\boldsymbol{m}_{pm}\| \|\boldsymbol{v}\|}{4\pi \|\boldsymbol{r}^4\|} \cos(2\theta - \phi) \tag{6}$$

Therefore the power loss is maximized when $2\theta - \phi = 0$, or $\phi = 2\theta$. Thus, the optimal orientation of the permanent magnet is

$$\hat{\boldsymbol{m}}_{pm} = \begin{bmatrix} \cos(2\theta) \\ \sin(2\theta) \end{bmatrix} \tag{7}$$

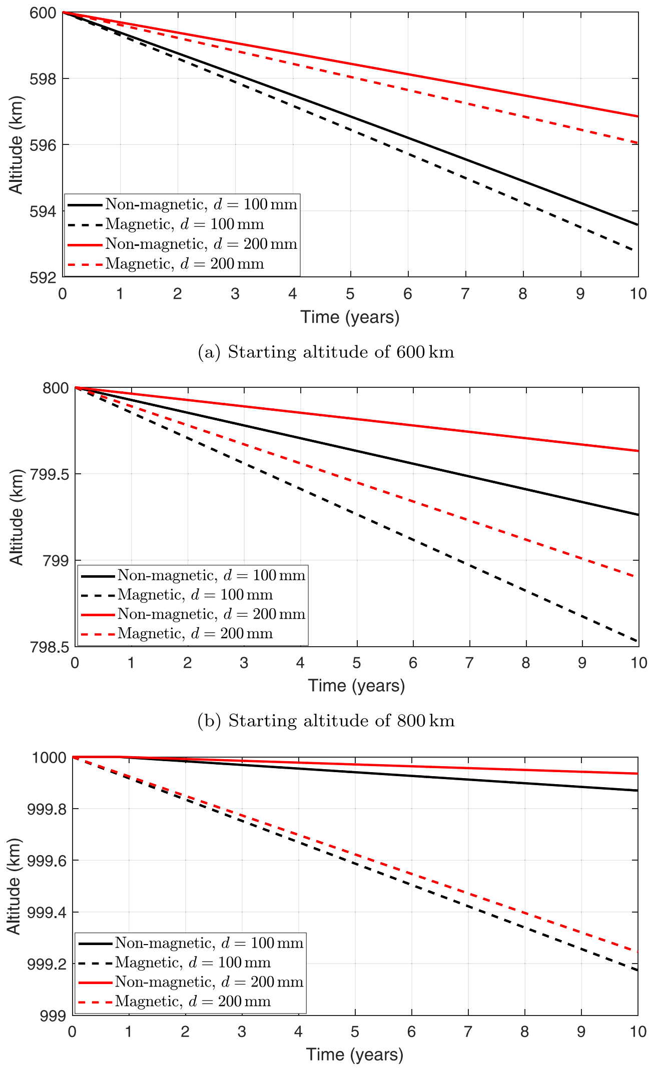
One might have expected that the optimal permanent-magnet orientation would be the orientation that causes the magnetic force to be in the negative velocity direction ($\hat{\boldsymbol{f}}_m = -\hat{\boldsymbol{v}}$) since forces perpendicular to velocity do not remove energy from the system, in which case we could use

$$\hat{\boldsymbol{m}}_{pm} = \frac{\mathbb{Q}^{-1} \hat{\boldsymbol{f}}_m}{\|\mathbb{Q}^{-1} \hat{\boldsymbol{f}}_m\|} \tag{8}$$

to solve for the permanent magnet's orientation. However, this would be slightly suboptimal because the magnitude of the force changes with ψ, and we therefore need to find the permanent-magnet orientation that maximizes the component of force in the negative velocity direction (i.e., that minimizes power in (5)). In Fig. 2(a), we show the nondimensional power

$$\tilde{P} = \frac{4\pi \|\boldsymbol{r}\|^4}{3\mu_0 \|\boldsymbol{m}_E\| \|\boldsymbol{m}_{pm}\| \|\boldsymbol{v}\|} P \tag{9}$$

using the two forcing methods described above; this nondimensionalization makes the results invariant to the specific orbit and permanent magnet selected. In Fig. 2(b), we show the associated permanent-magnet orientation. We verify that simply directing the force opposite



(a) Starting altitude of 600 km

(b) Starting altitude of 800 km

(c) Starting altitude of 1000 km

Fig. 4. Comparison of altitude vs. time for an optimally oriented permanent magnet and an otherwise-equivalent non-magnetic object of two sizes, starting at three altitudes.

to the velocity is suboptimal. It is also interesting to note that the optimal power loss is invariant to θ.

In addition to the magnetic force, a gravitational force and drag force also act on the orbiting permanent magnet. The gravitational force is

$$\boldsymbol{f}_g = -\frac{\mu}{\|\boldsymbol{r}\|^2}\hat{\boldsymbol{r}} \tag{10}$$

The drag force is

$$\boldsymbol{f}_d = -\frac{1}{2}\rho c_d S \|\boldsymbol{v}\|^2 \hat{\boldsymbol{v}} \tag{11}$$

where ρ is the density of the air, c_d is the drag coefficient, and S is the reference area.

3. Materials and methods

In order to determine the feasibility of utilizing Earth's magnetic field to de-orbit a RSO with an attached permanent magnet, using the best-case assumptions described previously, we created a simulation that numerically integrates the equations of motion for an orbiting

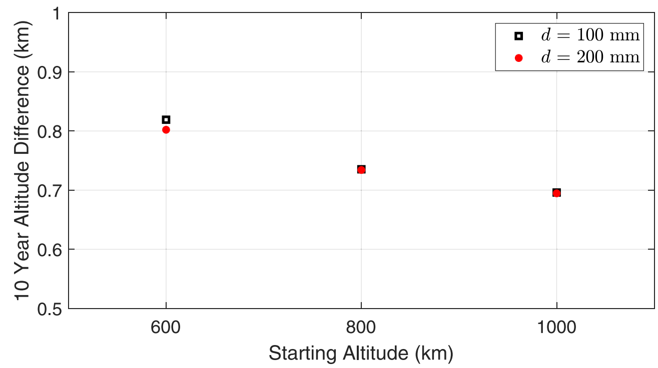


Fig. 5. Difference in the change of altitude over 10 years of an optimally oriented permanent magnet and an otherwise-equivalent non-magnetic object of two sizes, starting at three altitudes.

spherical permanent magnet under the influence of magnetic (2), gravitational (10), and drag forces (11). The simulation takes the permanent magnet's initial position and size as inputs. The simulation then propagates the permanent magnet's position forward in time until it reaches a user-defined simulation end time or collides with the surface of Earth. The simulation makes the following assumptions:

- The permanent magnet is a sphere parameterized by diameter d. It has a volume $V_{pm} = \pi d^3/6$, a reference area of $S = \pi d^2/4$, and a drag coefficient of $c_d = 2$ [10].
- The magnetization of the permanent magnet is $M_{pm} = 10^6$ A m^{-1}, and its density is 7500 kg m^{-3}, which are values typical of NdFeB. The permanent magnet's dipole strength and mass are both linearly proportional to its volume.
- Earth's magnetic field can be modeled as a dipole field of strength $\|\boldsymbol{m}_E\| = 8 \times 10^{22}$ A m^2 [11]. $\boldsymbol{m}_E$ is parallel with the y-axis of the coordinate frame.
- A combined density model from [12] is used to calculate atmospheric density ρ as a function of altitude (see Appendix B for more details).

With the user inputs specified, the simulation will then run the pseudocode shown in Fig. 3. The simulation uses a Stormer-Verlet geometric integrator [13] to propagate the orbit forward in time using Newton's 2nd law ($\Sigma \boldsymbol{f} = m\boldsymbol{a}$). Permanent-magnet orientations are set optimally, as described in Section 2.

The simulation was used to analyze the ability of a permanent magnet to de-orbit an RSO. We ran simulations, using the optimal forcing direction, for starting altitudes of 600 km, 800 km, and 1000 km. We considered permanent magnets of two different sizes: d = 100 mm and d = 200 mm. In order to have a baseline to compare against, a non-magnetic RSO was also simulated; this object had the exact same properties as the orbiting permanent magnet, but with the magnetic force turned off in the simulation.

4. Results and discussion

The results of our simulation, presented in the form of altitude (when passing over the magnetic south pole) vs. time over a 10-year period, are shown in Fig. 4. From these results, the decrease in altitude at the 10-year mark that can be attributed to the magnetic force is shown in Fig. 5. The decrease in altitude that can be attributed to the magnetic force (which we find is effectively invariant to the size of the object) is 0.81 m, 0.73 m, and 0.69 m for starting altitudes of 600 km, 800 km, and 1000 km, respectively.

These results indicate that using the interaction between a permanent magnet and Earth's magnetic field is not a viable option for de-orbiting space debris. Although optimally applied magnetic forces

Table B.1
Atmospheric density model parameters [12].

Altitude section	h_i (km)	ρ_i (kg m^{-3})	a	δ_h
$84 \le h \le 90$ km	95	7.726×10^{-6}	0.1545455	197.9740
$90 < h \le 106$ km	99	4.504×10^{-6}	0.1189286	128.4577
$106 < h \le 120$ km	110	5.930×10^{-8}	0.5925240	4328.8484

will decrease the time that an object takes to de-orbit, it is by a negligible amount. For example, for a circular orbit that starts at 1000 km, our proposed de-orbiting method would take over 800 years to successfully de-orbit the permanent magnet (without any additional RSO mass). The trends in the data suggest that starting altitudes higher than 1000 km will having even less favorable results. In this work, we only examined circular orbits, but we have tested a few cases of non-circular orbits and found results of similar orders of magnitude.

Interestingly, we found that altitude change attributed to the magnetic force is on the same order of magnitude as the altitude loss due to drag over any given duration of time. This suggests that there may be some merit to using an actively controlled permanent magnet for station keeping of an active RSO, although the control policy to direct the magnetic force will be different than what we have considered here. The feasibility of such an approach is left as an open question.

CRediT authorship contribution statement

Devin K. Dalton: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Jake J. Abbott:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Henry C. Fu:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Air Force Research Laboratory, United States, Aerospace Systems Directorate, Rocket Propulsion Division under Educational Partnership Agreement 20-EPA-RQ-50.

Appendix A. Linear mapping of the permanent-magnet dipole vector to magnetic force vector

If we parameterize as $\hat{\boldsymbol{r}} = [\hat{r}_x \ \hat{r}_y]^\top$ and $\boldsymbol{m}_E = [m_{E_x} \ m_{E_y}]^\top$, it can be shown that the magnetic force $\boldsymbol{f}_m$ of (2) can be expressed as a linear function of $\boldsymbol{m}_{pm}$ as shown in (3), using

$$\mathbb{Q} = \frac{3\mu_0}{4\pi\|\boldsymbol{r}\|^4}\begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22}\end{bmatrix} \tag{A.1}$$

$$q_{11} = 3\hat{r}_x m_{E_x} + \hat{r}_y m_{E_y} - 5\hat{r}_x(\hat{r}_x^2 m_{E_x} + \hat{r}_x\hat{r}_y m_{E_y}) \tag{A.2}$$

$$q_{12} = \hat{r}_x m_{E_y} + \hat{r}_y m_{E_x} - 5\hat{r}_y(\hat{r}_x^2 m_{E_x} + \hat{r}_x\hat{r}_y m_{E_y}) \tag{A.3}$$

$$q_{21} = \hat{r}_x m_{E_y} + \hat{r}_y m_{E_x} - 5\hat{r}_y(\hat{r}_x^2 m_{E_x} + \hat{r}_x\hat{r}_y m_{E_y}) \tag{A.4}$$

$$q_{22} = \hat{r}_x m_{E_x} + 3\hat{r}_y m_{E_y} - 5\hat{r}_y(\hat{r}_x\hat{r}_y m_{E_x} + \hat{r}_y^2 m_{E_y}) \tag{A.5}$$

It is straightforward to verify that $\mathbb{Q}$ is always invertible by searching over $0° \le \theta < 360°$, with $\hat{r}_x = \cos\theta$ and $\hat{r}_y = \sin\theta$.

We note that, in this paper, we exclusively consider $\boldsymbol{m}_E$ parallel with the y-axis, such that $m_{E_x} = 0$ and $m_{E_y} = \|\boldsymbol{m}_E\|$.

Appendix B. Atmospheric density model

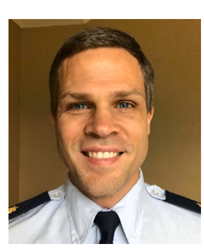
The density is calculated using a combined piecewise density model developed by Bettinger in [12]:

$$\rho(h) = \begin{cases} \rho_\oplus e^{-\beta}, & h < 84\,\text{km} \\ \rho_i\left[\left(1+\delta_h\left(\frac{h-h_i}{r_E}\right)\right)^{-1}\right]^{\frac{1+a}{a}}, & 84\,\text{km} \le h \le 120\,\text{km} \\ (4.50847623\times 10^7)h^{-7.44605852}, & 120\,\text{km} < h \le 1000\,\text{km}\end{cases} \tag{B.1}$$

For altitude h below 84 km, the density obeys an exponential atmospheric model, where $\rho_\oplus$ is the density at sea level (for Earth, $\rho_\oplus = 1.225$ kg m^{-3}) and β is the atmospheric scale height, which is a constant for any given planet (for Earth, $\beta = 0.14$ km^{-1}). The Earth is assumed to be a uniform sphere and therefore $h = r - r_E$. For altitudes between 84 km and 120 km, the density obeys the single variation model provided by [14], where the index i denotes different sections of the atmosphere and δ_h and a are constants for those sections of the atmosphere, listed in Table B.1. For altitudes above 120 km, the density is modeled as a rarefied atmosphere.

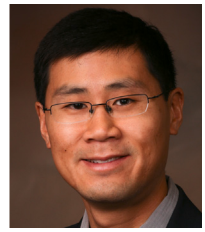
References

[1] N. Mohanta, How many satellites are orbiting around the Earth in 2022? 2023, URL: https://www.geospatialworld.net/prime/how-many-satellites-orbiting-earth, (Accessed 23 March 2023).
[2] ESA, Space debris, by the numbers, 2023, URL: https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers, (Accessed 21 April 2023).
[3] E.S.D. Office, ESA's Annual Space Environment Report, Technical Report GEN-DB-LOG-00288-OPS-SD, European Space Agency, 2022.
[4] FCC, FCC adopts new '5-year rule' for deorbiting satellites, 2022, URL: https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites, (Accessed 23 August 2023).
[5] NASA, State-of-the-Art Small Spacecraft Technology, Technical Report, Ames Research Center, 2022, p. 346.
[6] C.P. Mark, S. Kamath, Review of active space debris removal methods, Space Policy 47 (2019) 194–206.
[7] M.M. Castronuovo, Active space debris removal—A preliminary mission analysis and design, Acta Astronaut. 69 (2011) 848–859.
[8] J. Davis, Mathematical Modeling of Earth's Magnetic Field, Technical Report, Virginia Tech, 2004.
[9] J.J. Abbott, E. Diller, A.J. Petruska, Magnetic methods in robotics, Annu. Rev. Control Robot. Auton. Syst. 3 (2020) 57–90.
[10] M.D. Pilinski, S.E. Palo, An innovative method for measuring drag on small satellites, in: 23rd Annual AIAA/USA Conference on Small Satellites, 2009.
[11] NASA, Earth's inconstant magnetic field, 2023, URL: https://science.nasa.gov/science-news/science-at-nasa/2003/29dec_magneticfield, (Accessed 24 August 2023).
[12] R.A. Bettinger, The Prospect of Responsive Satellites Utilizing Atmospheric Skip Entry Maneuvers (Ph.D. thesis), Air Force Institute of Technology (AU), Wright-Patterson AFB, 2014.
[13] P.S. Guillaume Chauvon, A.V. Wouwer, An implementation of geometric integration within MATLAB, Simul. Trans. Soc. Model. Simul. Int. (2019).
[14] A.B. Nguyen X. Vinh, R.D. Culp, Hypersonic and Planetary Entry Flight Mechanics, The University of Michigan Press, Ann Arbor, 1980.



Devin K. Daltonreceived a B.S. degree in Mechanical Engineering from Utah State University, USA, in 2009, an M.S. degree in Aeronautical Engineering from the Air Force Institute of Technology, USA, in 2014, and a Ph.D. degree in Mechanical Engineering (Robotics Track) from the University of Utah, USA, in 2023. He is a Major in the United States Air Force.

Jake J. Abbott received a B.S. degree from Utah State University, USA, an M.S. degree from the University of Utah, USA, and a Ph.D. degree from Johns Hopkins University, USA, all in Mechanical Engineering, in 1999, 2001, and 2006, respectively. He was then a postdoctoral research associate at ETH Zurich, Switzerland until 2008, when he joined the faculty of the Department of Mechanical Engineering, University of Utah, USA, where he is now a Professor.



Henry C. Fu received an A.M. degree in Chemistry concurrently with an A.B. degree in Chemistry and Physics with a minor in Mathematics from Harvard University, USA, in 2000. He received a Ph.D. degree in Physics from the University of California, Berkeley, USA, in 2006. He was then a postdoctoral research associate at Brown University until 2010. From 2010-2016, he was Assistant Professor in the Department of Mechanical Engineering at the University of Nevada, Reno, USA. Since 2016, he has been a member of the faculty in the Department of Mechanical Engineering, University of Utah, USA, where is now a Professor.