Control Strategies Utilizing the Physics of Flux-Pinned Interfaces for Spacecraft

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Flux-Pinned Interfaces are a developing technology for spacecraft that exploit flux pinning, a phenomenon in superconducting physics, to manipulate the dynamics between two spacecraft modules. Flux pinning occurs in certain types of superconductors which, when cooled below their critical temperature, will resist changes to the distribution of magnetic flux that was present during the temperature transition. The resulting physics passively “pins” a magnetic field source in a six-degree-of-freedom equilibrium relative to the superconductor. By placing a magnetic array on one spacecraft module and a superconductor with this capability on another, it is possible to exploit these passive physics to augment technologies for close-proximity spacecraft operations such as rendezvous, docking, and formation flying. This paper investigates the use of the nonlinearities and specific physics in the flux pinning connection to develop efficient control strategies that will allow spacecraft operators to alter the equilibrium of a flux-pinned space system. Specifically, the dynamic model for flux-pinned spacecraft is presented, a set of design principles for actuators are examined with simulation plots to demonstrate the system response to various stimuli, and two potential control strategies are presented. The paper concludes with an assessment of the actuation strategies and potential advantages and disadvantages that each has to offer in the context of actual spacecraft operations.

Nomenclature

\begin{align*}
\hat{a} &= \text{superconductor surface normal} \\
\hat{A}_i &= \text{the area enclosed by the current loops in electromagnet } i \\
B_i &= \text{the magnetic field strength of magnet } i \text{ at its surface, in the dipole direction} \\
b &= \text{magnetic field} \\
c &= \text{linear damping coefficient} \\
C &= \text{vector from the center of mass of the spacecraft to the center of the plane containing the magnets} \\
d &= \text{the scalar distance from the center of a magnet to its surface, along the dipole axis} \\
D &= \text{the lateral (z-direction) relative distance between a rendezvous craft and its target} \\
e &= \text{the error in the actual input as compared to the reference input} \\
[I]_i &= \text{inertia matrix of a magnet} \\
k_d &= \text{derivative gain} \\
k_i &= \text{integral gain} \\
k_p &= \text{proportional gain} \\
L_i &= \text{vector from the center of the plane containing the magnets to the center of mass of magnet } i \\
\mu_0 &= \text{permeability of free space} \\
n &= \text{dipole moment vector} \\
n_{FC,i} &= \text{dipole moment vector of magnet } i \text{ at field-cooling} \\
\hat{n} &= \text{dipole moment unit vector } n/|n| \\
r &= \text{inertial position vector}
\end{align*}

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\[ R_i = \text{the resistance of electromagnet } i \]
\[ \rho = \text{relative position vector from the image to its source} \]
\[ \rho_{m,i} = \text{relative position vector of a mobile image to its source magnet } i \]
\[ \rho_{f,i} = \text{relative position vector of a frozen image to its source magnet } i \]
\[ \rho_{f,2} = \text{relative position vector of magnet 1’s frozen image to magnet 2} \]
\[ T_i = \text{the number of turns in electromagnet wire } i \]
\[ W = \text{total number of magnets in an FPI system} \]
\[ V_i(t) = \text{voltage in electromagnet } i \text{ at a given time} \]

I. Introduction

CLOSE-PROXIMITY spacecraft operations, including maneuvers such as autonomous rendezvous and docking, formation flying, and on-orbit reconfiguration and servicing, are becoming increasingly critical to the future of space systems. The ability to operate multiple spacecraft next to one another on the order of meters or less offers expanded functionality that is difficult to achieve otherwise and, when combined with spacecraft modularity, may provide added longevity and more adaptability to spacecraft in the coming decades.

Nevertheless, these operations are often fraught with the risk of costly collisions; thus, there is considerable interest in research devoted to finding robust and efficient methods of controlling spacecraft in close proximity in the presence of failures and uncertainties. Despite the advancements made in these areas, the limitations of autonomous routines and current control strategies were strikingly exposed in 2005 in the case of the DART (Demonstration of Autonomous Rendezvous Technology) mission, where errors in the guidance, navigation, and control software caused the spacecraft to collide with its intended rendezvous target.

One technology currently under development may help bypass some of these vulnerabilities by passively augmenting a close-proximity space system with a familiar phenomenon in superconducting physics: magnetic flux pinning. Type-II superconductors cooled below their critical temperature (88K for YBCO) resist changes in the magnetic flux within their volume from the distribution that was present during the temperature transition (a process known as field-cooling). The result is a non-contacting interaction between magnetic field sources and these types of superconductors that can be used to “pin” magnetic sources into a passively stable six-degree-of-freedom equilibrium relative to the superconductor, as seen in Figure 1. This equilibrium remains set as long as the superconductor remains below its critical temperature, leading to the possibility that on a sun-shielded portion of a spacecraft, this effect would remain without the use of any power.

Research into flux pinning applications, especially of high-temperature superconductors such as Yttrium Barium Copper Oxide (YBCO), is predominantly focused on levitating items in a 1-g environment, such as in superconducting bearings or MAGLEV trains, but some work has been done in six degrees of freedom, such as applications of finely actuated robotic wrists. However, flux pinning has a number of traits that make it well-suited to close-proximity applications in a space environment that are just now being thoroughly explored. For example, flux pinning exhibits a range of stiffness and damping values that vary by the strength of the magnetic field, and studies have shown that the stiffness is sufficient to withstand the magnitude of perturbation forces and torques found in the space environment. The nonlinear forces involved in the interface also allow a flux-pinned system to resist collisions, since the interface pushes the system to equilibrium with increasing force as the distance between the superconductor and magnet becomes smaller. This effect can provide an impact attenuation effect in a flux-pinning augmented docking interface.

Figure 1. A Neodymium permanent magnet (bottom) flux pinned to a disk of YBCO superconductor (top) which has been cooled by liquid nitrogen to below its critical temperature of 88 K.
Advantages such as these have triggered an interest in the development of a flux-pinned interface (FPI) technology for spacecraft, where one spacecraft module has a magnetic field array and another contains a cooled superconductor imprinted with a desired equilibrium as shown in Figure 2. While this interaction will maintain a passive stability at the set equilibrium, the ability to actuate this equilibrium provides more flexibility to satellite operators and can better accommodate on-orbit realities. Thus, the focus of this paper is to develop a series of actuation principles that work with the dynamics set up by flux-pinning physics between two spacecraft, and then use those dynamics to suggest a series of control strategies. The first section provides an overview of the relevant elements of the controlled system: the actuators, plant model, and simulation parameters used for this evaluation (for the purposes of this paper, the sensing is assumed to provide perfect state knowledge, so is not examined in more depth). The following section then describes a set of design principles for the actuation of an FPI, and the subsequent section describes a sample of controllers that exploit the physics of the flux-pinned. A set of conclusions summarizes the design strategies and evaluates their potential for useful implementations on spacecraft hardware.

II. Flux-Pinned Spacecraft Control Elements

A. Flux-Pinned Interface Design and Actuation

A flux-pinned interface for spacecraft in its simplest form involves a single superconductor cooled to below its critical temperature and mounted onto one spacecraft module, and a single magnetic field source mounted on another module. A FPI can be designed with other superconductor or magnet configurations in order to perform certain functions more efficiently. For example, magnetic field sources that are axisymmetric experience no stiffness in the degree of freedom associated with that symmetry because the superconductor only resists changes in the magnetic flux. Since a cylindrical magnet spinning about its axis has no change in magnetic flux in that direction,
the superconductor does not react against the motion. Thus, a properly designed FPI that exploits this phenomenon can be used to create a flux-pinned hinge, or other kinematic mechanisms. This principle is illustrated in Figure 3, a configuration which has been successfully implemented in hardware on both a 3-degree-of-freedom air table and in a microgravity environment. The controller for this type of FPI is mostly limited to static “rotate clockwise” and “rotate counterclockwise” commands that involve switching the polarity of the electromagnets.

Alternatively, in applications such as a rendezvous interface where 6 degree-of-freedom stiffness is preferred and fine-tune actuation or stationkeeping is desired, the FPI typically includes two magnetic elements: an asymmetric array of permanent magnets that provides stiffness in all degrees of freedom and guarantees of stability even in a power failure case and an array of electromagnets for actuating the equilibrium in multiple degrees of freedom (the specific design for this paper is described in a subsequent section). This type of FPI has been successfully demonstrated on a three-DOF air bearing testbed, as illustrated in Figure 4.

The properties of the FPI depend on a number of factors, but the most direct way to influence the equilibrium position is to manipulate the magnetic field. For example, the maneuver in Figure 5(a), activating an electromagnet that was not powered during the field-cooling process (zero field-cooled) causes repulsion from the superconductor because more flux is now present than was during the critical temperature transition, so the superconductor resists the excess flux. However, the strong basin of attraction provided by the permanent magnet allows an equilibrium to be maintained, just in an altered configuration.

Another way to actuate the equilibrium is to adjust the current in an electromagnet, which affects the strength of the magnetic field it produces. Using this principle, it is possible to actuate the equilibrium position as shown in Figure 5(b). More intricate arrangements of magnetic field sources can be used to map to different degrees of freedom, although the nonlinearities inherent in magnetic field sources makes this mapping ripe with couplings and other complexities. Thus, these more elaborate actuation methods are left to simulation. Understanding actuation principles such as these is the purpose of this paper.

### B. Modeling the Flux-Pinned Spacecraft Plant

Many magnetic effects can be modeled using “images”, where the interaction forces and torques are approximated as the analytical solution for the magnetic force and torque exerted by one magnet on its “image,” which has a defined magnitude and position depending on the effect being modeled. Magnetic flux pinning is no exception: in 1997 Kordyuk published a frozen-image model to approximate the forces and torques between an infinite hard superconductor without hysteretic or edge effects and a perfect dipole magnet.
This model suggests that each magnetic field source outside of the superconductor during the critical temperature transition creates two images within the superconductor: a frozen image and a mobile image. The frozen image is fixed in place in a distance reflected across the surface of the superconductor from the field-cooling position and provides a basin of attraction for the magnet’s equilibrium position. The mobile image, on the other hand, moves with the magnet in real time, with a distance that is also reflected over the surface of the superconductor. However, this image has an opposite dipole orientation of the magnet, causing a repulsion force to act on the magnet when it is not in its equilibrium position.

This model has been adapted to a simplified spacecraft FPI using variables as listed in Figure 6. However, in order to fully develop the equations for testing various controllers, it is necessary to detail the equations governing electromagnets and to fully characterize the total effect of the magnetic sources and their images on the spacecraft.

The total forces and torques acting on magnet 1 in the spacecraft as a result of the FPI can be described as:

\[ \mathbf{F}_{\text{tot}_{-1}} = \sum_{i=1}^{w} \mathbf{F}_{\text{im}_{-1}} + \mathbf{F}_{\text{f}_{-1}} \]  

\[ \mathbf{T}_{\text{tot}_{-1}} = \mathbf{p}_i \times \mathbf{F}_{\text{tot}_{-1}} + \sum_{i=1}^{w} \mathbf{T}_{\text{im}_{-1}} + \mathbf{T}_{\text{f}_{-1}} \]

where \( i \) is the current magnet, \( w \) is the total number of magnets in the FPI, and the subscript \( m \) represents the force or torque induced by the mobile image and the subscript \( f \) implies the force or torque induced by the frozen image.

The general formulation for each force and torque in due to the mobile image (of mobile image on magnet \( b \)) as listed in Equations (1) and (2):

\[ \mathbf{F}_{\text{am}_{-b}} = \frac{3\mu_0 n_{m-a} n_b}{4\pi\rho_{am}^4} \left[ \hat{\mathbf{p}}_a \left( \hat{\mathbf{n}}_{m-a} \cdot \hat{\mathbf{n}}_b \right) + \hat{\mathbf{n}}_{m-a} \left( \hat{\mathbf{p}}_m \cdot \hat{\mathbf{n}}_b \right) + \hat{\mathbf{n}}_b \left( \hat{\mathbf{p}}_m \cdot \hat{\mathbf{n}}_a \right) - 5\hat{\mathbf{p}}_m \left( \hat{\mathbf{p}}_m \cdot \hat{\mathbf{n}}_{m-a} \right) \left( \hat{\mathbf{p}}_m \cdot \hat{\mathbf{n}}_b \right) \right] \]

\[ \mathbf{T}_{\text{am}_{-b}} = \frac{\mu_0 n_{m-a} n_b}{4\pi\rho_{am}^3} \left[ 3 \left( \hat{\mathbf{n}}_{m-a} \cdot \hat{\mathbf{p}}_m \right) \left( \hat{\mathbf{n}}_b \times \hat{\mathbf{p}}_m \right) + \left( \hat{\mathbf{n}}_{m-a} \times \hat{\mathbf{n}}_b \right) \right] \]

where \( \mu_0 \) is the permeability of free space, \( n \) is the magnetic dipole moment vector magnitude, \( \hat{\mathbf{n}} \) is the magnetic dipole unit vector, and \( \mathbf{p}_a \) is the vector from the mobile image under consideration to the magnet. The values for the mobile and frozen magnetic dipole moments are:

\[ \hat{\mathbf{n}}_{m-i} = (\hat{\mathbf{n}}_i - 2(\hat{\mathbf{a}} \cdot \hat{\mathbf{n}}_i)\hat{\mathbf{a}}) \]

and

\[ \hat{\mathbf{n}}_{f-i} = 2(\hat{\mathbf{a}} \cdot \hat{\mathbf{n}}_{FC,i})\hat{\mathbf{a}} - \hat{\mathbf{n}}_{FC,i} \]

where \( \hat{\mathbf{a}} \) is the surface norm of the superconductor and FC represents the quantity at field cooling. For a permanent magnet, the magnetic dipole moment magnitude is:

\[ \hat{\mathbf{n}}_i = \left( \frac{2\pi B d_i^3}{\mu_0} \right) \hat{\mathbf{n}}_i \]

where \( B \) is the surface strength of the magnetic field of the dipole measured along its axis and \( d_i \) is the distance from the center of the magnet to its surface. However, for an electromagnet, this expression becomes:
\[ n_i = \left( \frac{V_i(t)A_T}{R_i} \right) \hat{n}_i \]

where \( V_i(t) \) is the voltage applied across the electromagnet as a function of time, \( A_i \) is the area enclosed by the electromagnet’s current loop, \( T_i \) is the number of turns in the electromagnets, and \( R_i \) is the resistance of the electromagnet. Thus, given the geometry of the system, the initial conditions and the field-cooling conditions, this model can be applied to a wide variety of FPI configurations with both permanent and electromagnets.

C. Simulation Parameters

Evaluating different system geometries and field-cooling conditions is outside the scope of this work, so a baseline configuration has been established in order to provide a basis of comparison among the different controllers and actuation techniques. It is possible that the selection of these specific values may favor a particular controller over another; thus, sensitivity studies to these variables will need to be examined in future work.

The particulars of this baseline configuration were chosen to match the values of the FPI flight-demonstration module from project RAGNAR (Robust Autonomous Grappler for Non-contacting Actuation and Reconfiguration), seen in Figure 7. This project implemented a FPI on a CubeSat-scale spacecraft module and flew it on NASA’s Sept 30 – Oct 1 FAST microgravity flight. By choosing to simulate parameters that are similar to already constructed hardware, future controller validation can easily be moved to a hardware-in-the-loop system employing the RAGNAR module and an air bearing testbed developed in Cornell’s Space System Design Studio.

The CubeSat module has a mass of approximately 2 kg, and the inertia estimate (obtained from CAD models) is:

\[ I_{cube} = \begin{pmatrix} 0.00883 & -0.00016 & 0.00003 \\ -0.00016 & 0.0101 & -0.00001 \\ 0.00003 & -0.00001 & 0.00936 \end{pmatrix} \text{ kg} \cdot \text{m}^2 \]

The cube is simplified to 10 cm on a side in the software, although the actual hardware is slightly larger.

The geometry of the magnetic side of the interface is shown in Figure 8. Two Neodymium permanent magnets (brown in the figure) are aligned in the middle to create passive stiffness in all degrees of freedom. They have the same dipole direction and magnitude. The magnetic field strength at their surface (which is 0.00635 m from the center of the magnet) is given as 0.5233 Tesla by their specifications sheet. These two magnets are ringed by four identical electromagnets (dark grey in the figure), which have an internal resistance of 38Ω, an area of 5.1e-4 m², and 5000 turns. All of the electromagnets are wired such that positive voltages produce the same direction of magnetic dipole as the permanent magnets. The electromagnets have the capacity to receive ±15 V, and are simulated as if they had 10 V during field cooling. The plate containing the magnets is simplified to approximately 5 cm from the center of mass of the cube, but the vectors describing the positions of the magnets on the plane are taken directly from the CAD model.

Fielding cooling is simulated as taking place at a 1 cm separation distance between the superconductor surface and the plane of the magnets, but zero relative rotation between them. The damping coefficient \( c \) is 0.2.
III. Actuation Design Principles

A. Field-Cooling Actuators

Because of the unique physics of flux pinning, the setup of the interface during the cooling process has a significant influence on the behavior of the system once the FPI is in place. One approach to this design decision is to leave the electromagnetic actuators off during the field-cooling process, and then using their non-zero field to actuate the system. This zero field-cooled actuator only has the ability to repel the superconductor, since the superconductor will not have frozen image for the actuator to provide a basin of attraction. However, despite the fact that the magnet can only repel the superconductor, the electromagnet and its mobile image still interact with the permanent magnets in the system. Thus, using a positive and negative voltage for a zero field-cooled actuator will actually produce different equilibriums, especially along the line between the permanent magnet and the electromagnet (in this case, the y direction) as shown in Figure 9. This particular maneuver also excites modes in the z and y position, and induces and angular rate about the x axis. This particular type of actuator design is particularly well suited to maneuvers where the system is only desired to move in one particular direction (for example, in a docking interface where motion in one direction represents a collision).

On the other hand, FPIs offer flexibility in the design if bi-directional motion is required. If the system is field-cooled with an electromagnet actuator at some constant state (for example, 10 V), the system can then produce symmetric actions in both the positive and negative directions, as shown in Figure 10. When the actuator is field-cooled into a position, the response is a predictable change in position and angle. The system still excites modes in the z and the y positions, but the resulting equilibrium is significantly different. This type of actuator design is best suited to a vibration-isolated non-contacting pointing platform, such as one that might be used in the pointing of mirror segments in a large aperture telescope, where this flexibility and symmetry may be most useful.

Figure 9. The system x and y and quaternion response for a zero field-cooled actuator where the dashed red and green lines represent a negative 0.5 V and solid lines represent a positive 0.5 V.

Figure 10. The system x and y and quaternion response for a field-cooled actuator where the dashed lines represent a negative 0.5 V from the field-cooled voltage and solid lines represent a positive 0.5 V.
B. Strength of Actuation

The current in the electromagnets dictates the strength of the magnet and thus affects the stiffness of the FPI connection. Assuming that all of the actuators are field-cooled at 10 V, the frequency response when actuating all of the electromagnets together, at various voltage levels, is shown in Figure 11. Actuators with voltages higher than their field-cooled levels produce a strong response that triggers modes in a number of different directions. The frequency response shows that the dominant peaks are at much higher amplitudes for voltages above the field-cooled value, due to the strength of the magnets and a shift to a lower frequency. This is the result of the magnets being repelled to a further equilibrium to account for their new strength. For voltages lower than the field-cooled values, however, the dominant frequency is shifted higher as a result of the weaker magnets shifting to a closer equilibrium in an attempt to re-establish the flux distribution when the magnets were stronger. The raising and lowering of the voltage from the field-cooled equilibrium can be useful in tuning the natural frequency of the system, as well as setting up new equilibriums that are closer or further from the original field-cooled position.

The lowest natural frequencies are seen when the voltage is an order of magnitude lower than that of the field-cooled position. The polarity of the electromagnet appears to have a small, but mostly irrelevant effect for simple frequency tuning. However, if the electromagnets of the opposite polarity are too strong, they repel off their own image very strongly and can send the magnet module out of the basin of attraction of the permanent magnet’s influence. Figure 12 shows this maneuver as values of -0.5 V, -1 V, and -1.4V are fed into all of the electromagnets field-cooled at 10 V. The system is excited until it reaches a point well beyond the influence of flux pinning of 15 cm (since the limitation of the flux pinning effect are not modeled, the system appears to continue to oscillate). This type of maneuver may be useful for releasing a docked module.

Further, if this particular actuation method is used, the system can be set to a zero voltage (no power) state at some desired altered equilibriums from the field-cooled position, allowing a system designer to set the equilibrium to a state that is different from the field-cooled state and yet does not require constant power usage.

Figure 11. The frequency response of a field-cooled actuation system at various magnet strengths, with the bolded plots at +15 V, the dashed plots at +5 V, the dotted (light) plots at -0.1 V, and the solid (light) lines at +0.1V for the position (a) x, (b) y, and (c) z.

Figure 12. The z system response for all electromagnets being tuned to increasing values of voltage that are of the opposite polarity as their field cooled condition.
C. Electromagnet Pairings

Another actuation strategy that can be used to control an FPI is exploiting the geometry of the system – particularly symmetries and different electromagnetic pairings – to produce desired results. For example, Figure 13 shows two different pairings of electromagnets from the RAGNAR setup. Figure 13(a) represents a symmetric pairing that is in line with the system’s asymmetric permanent magnet array. The position and quaternion results of pulsing these two electromagnets from off to different voltages (from a field-cooled +10V) are shown in Figure 14. Figure 13(b), on the other hand, represents an asymmetric pairing that excites more complex interactions and more degrees of freedom. The position and quaternion results of pulsing these two values to a variety a voltage values are shown in Figure 15.

Clearly, a symmetric actuation sequence excites fewer degrees of freedom and performs a clearer maneuver, which may be preferable for systems where complexity in the system response is not necessary or not desired (such as in pre-programmed sequences). This maneuver also appears to produce higher overall displacement values from the equilibrium, since all of the actuation is going into a single degree of freedom, rather than being distributed among many. An asymmetric maneuver, however, has a more complex response that causes motion in multiple degrees of freedom and an asymmetric equilibrium in position and orientation. This type of response may be best suited to a maneuver that must respond to perturbations or other changing situations that requires more subtlety and complexity.

Figure 13. Different magnet pairings that can be exploited in the FPI design.

Figure 14. The system (a) x and y and (b) quaternion response for a 10V field-cooled actuator paired as Figure 13a over a variety of different field strengths.

Figure 15. The system (a) x and y and (b) quaternion response for a 10V field-cooled actuator paired as Figure 13b over a variety of different field strengths.
It is also interesting to note that the symmetry of the actuators is not related to the displacement symmetry of the possible maneuvers. For example, both the symmetric and asymmetric actuations are capable of producing the same types of displacement maneuvers in the positive and negative displacement directions (by using more or less voltage than the field-cooled state). Thus, although the geometry combinations in a system with a large number of magnets may be complicated, by way of these simple examples it can be seen that symmetric actuator pairings can produce more displacement and cleaner maneuvers, but will be less adept at handling complex maneuvering that may be required for reactive (rather than planned) adjustments.

IV. Control Strategies for a Flux-Pinned Interface

A. Linear ID Controller (No Proportional Gain)

Flux-pinning is unique in that it can avoid the implications of Earnshaw’s theorem, which states that a body subject to any combination of only inverse-square forces must use active control to remain stable in an arbitrary equilibrium. This property of flux pinning is perhaps the most obvious element of the physics that can be exploited for engineering purposes. In Figure 16 the system is not actively controlled yet the behavior of the system is stable in the presence of an initial 0.8 cm offset in the lateral (z) and in the y transverse positions from the equilibrium.

Thus, since the FPI is already maintaining an equilibrium position, it may be possible to implement a fine-tuning controller over an FPI with just an integral and derivative portion, while letting the physics compensate for the proportional portion of the controller. The primary advantage of this formulation is that it conserves control input (which is ultimately a resource cost onboard a spacecraft) while still providing tuning options for the spacecraft operator to manage the overshoot and steady state error in the response.

$$u(t) = k_i \int_0^t e(\tau) d\tau + k_d \frac{d}{dt} e(t)$$

where \( e \) is the error in the output when compared to the reference input.

B. Lateral Distance-Dependent Gain

In docking applications, the lateral distance between the rendezvous spacecraft and its target are of particular concern, given the high costs associated with collisions. During close proximity operations, the controller is responsible for exerting the forces necessary to avoid a collision, and in the case of large errors in the relative position of the two

Figure 17. A depiction of the nonlinear potential well of a flux-pinned magnet near a superconductor (shown as a dark wall).
craft, the control effort may need to be significant. Having an FPI-augmented docking system may help relieve this burden on the controller, in addition to being robust to sensing, power (assuming permanent magnets are used), and guidance failures. Because flux pinning responds to a decreasing relative distance between a field-cooled magnetic field and a superconductor with a nonlinearly increasing force (depicted by the potential well in Figure 17)\(^2\), it provides a majority of the necessary force to avoid unintentional contact between the two modules. Thus, the controller can conserve control effort by not exerting as much force in this regime. However, the potential well is much shallower when the relative distance increases, resulting in a much weaker force attempting to return to equilibrium. If it is equally as important to avoid the modules drifting apart, the controller will need to have much stronger response in this regime where the FPI has less of an effect. This conclusion leads to a controller where:

\[
 u(t) = k_p(D)e(t) \tag{11}
\]

where \(D\) is the relative distance between the center of the target’s plane and the center of the FPI plane on the rendezvous spacecraft. The actual mapping between the relative distance and the gain can take many forms, with the obvious choices being linear, exponential, or power series.

V. Conclusion

Flux-Pinned Interfaces for spacecraft are maturing rapidly as a technology, and have the potential to add a number of previously unattainable benefits to close-proximity spacecraft operations. However, in order to realize the full set of advantages that FPIs offer, it is important to intelligently design controllers around the physics of flux pinning. Using the frozen-image model proposed by Kordyuk, a plant model was developed that represented the behavior of flux pinning with multiple magnets onboard a spacecraft. With parameters taken from the RAGNAR flight project, simulations were constructed to demonstrate a number of different actuator design principles including the field-cooling of the magnet, the actuator field strength, and the electromagnet pairings.

Choosing whether to field-cool electromagnetic actuators can give different properties to the FPI once it is established. A zero field-cooled actuator will always repel the superconductor while still interacting with permanent magnets in the system based on its polarity, while a field-cooled electromagnet can offer bi-directional motion capability to the system. The strength of the electromagnet (determined by the amount of current) produces different responses in an FPI when the voltage is higher or lower than its field-cooled level. A higher voltage will push the magnet further from the field-cooled equilibrium, a lower voltage will bring it closer, and the opposite polarity will strongly repel the actuator, even pushing it out of the basin of attraction if the magnetic force is too strong. The magnet geometry can be used to produce equilibriums in very specific directions.

These design principles lead to two different controllers that attempt to exploit these physics: a linear ID controller and a nonlinear approach that takes lateral-distance values into account in the gain. Clearly, the response of these controllers to specific geometries and field-cooling configurations is of much interest and needs to be investigated. The accuracy of the model should be validated against actual controller performances with hardware-in-the-loop, and estimates should be made of the inaccuracies associated with edge effects, non-dipole magnets, and other assumptions.

Acknowledgments

L. Jones thanks the National Science Foundation for sponsoring this research, as well as Jillian Gorsuch for her tireless contributions to the RAGNAR project, and the support of the entire Space Systems Design Studio group.

References