Engineering Notes

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Reconfigurable Spacecraft as Kinematic Mechanisms Based on Flux-Pinning Interactions

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Nomenclature

\[ a = \text{incidence matrix arc (joint) index} \]
\[ i, j, k = \text{incidence matrix body indices} \]
\[ \mathcal{J} = \text{multibody spacecraft Jacobian} \]
\[ n = \text{number of bodies comprising a modular spacecraft} \]
\[ S = \text{multibody incidence matrix} \]
\[ u = \text{arcs (joints) linking each body of a multibody spacecraft} \]
\[ \delta_p^g = \text{flux-pinned interface connectivity parameter} \]

I. Introduction

The challenges of the space environment require that spacecraft exhibit a high degree of mission assurance, which often takes the form of autonomous fault tolerance [1,2]. However, the technology for spacecraft repair and reconfiguration missions has not yet matured to the point where autonomous operations are also robust. Many completed and envisioned spacecraft reconfiguration or repair techniques involve substantial human-in-the-loop activity, including Advanced X-Ray Astrophysics Facility servicing activities and Hubble Space Telescope repair and expansion missions [3]. Another example is the construction of the International Space Station, which astronauts have assembled and reconfigured piecemeal during many hours of extravehicular activity. Fully autonomous repair and reconfiguration tasks have been achieved only recently, such as on the Orbital Express mission [4], with extensive sensing and active control solutions [5]. We propose to depart significantly from traditional approaches to reconfiguration by treating modular, reconfigurable spacecraft as kinematic mechanisms. This proposal addresses the need for robust reconfiguration techniques in space without treating the problem of reconfiguration as one of docking or formation flight. In so doing, its approach incorporates passively stable physics, involving little to no active control at the level of the interface between modules and focusing on architectural control of the system start and end states.

Section II of this Note identifies some mathematical tools for treating reconfigurable spacecraft systems as kinematic mechanisms. This Note develops its treatment in the particular context of a reconfigurable system using FPI technology, but the kinematic-mechanism concept may be extended to other architectures as well. Section III then provides some examples of spacecraft reconfiguration through kinematic-mechanism techniques. The examples include detailed descriptions of two reconfiguration sequences for changing the order and relative orientation of a line of modules, as well as an air-table demonstration of a simple FPI-based reconfiguration.

II. Reconfiguration Mechanisms

The key concept motivating this approach is that spacecraft reconfiguration may be achieved through a combination of kinematics and passive dynamics by deterministically defining
physical equilibria to prescribe a stable sequence of configurations. That is, rather than a feedback control law driving a spacecraft system from one configuration to another based on a state-error estimate, the spacecraft system incorporates a sequence of kinematic constraints that permit only reconfiguration to the desired end state. This process opens up the possibility of passive reconfiguration, where active control or power inputs are not required. Instead, a modular spacecraft may obtain the energy it needs to reconfigure from its equilibrium spin state, gravity gradient, or small perturbations of the spacecraft momentum. If the mechanism imposes an appropriate set of kinematic constraints, the spacecraft must reconfigure to a desired end state by virtue of torque-free rigid-body motions.

An incidence matrix describes connectivity among the elements of a multibody system, based on the graph structure of the system [15]. For a modular system with a tree structure connected by flux-pinned interfaces, the incidence matrix takes the following form:

$$\begin{bmatrix}
S_0 & u_1 & u_2 & \cdots & u_n & 0 \\
S_1 & -1 & \delta_{12}^0 & \cdots & \delta_{1n}^0 & 0 \\
\vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
S_n & 0 & \delta_{n2}^0 & \cdots & \delta_{nn}^0 & 0
\end{bmatrix}$$ (1)

$S_0, \ldots, S_n$ designate each body in the system (where $S_0$ is a fictitious base body) and $u_1, \ldots, u_n$ designate the joints linking each body. We introduce the symbol $\delta_{ij}^0$, which suggests the Kronecker delta function, in place of constant matrix entries. These entries are parameters specifying the activity state of the flux-pinned interface represented by joint $a$. With the exception of the $S_0$ row and $u_i$ column, the incidence matrix of an FPI-linked system is generally filled with these parameters. If interface $u_i$ links body $S_j$ with $S_k$, then the parameters in column $a$ take the values

$$\delta_{ij}^0 = -1 \quad \delta_{ij}^0 = +1 \quad \delta_{ij}^0 = 0 \quad k \neq i, j$$ (2)

For $n$ bodies with pinning interfaces, there are $n^2$ such parameters, representing the potential for a flux-pinned interface to connect any two bodies and to reconfigure the incidence matrix. Of course, some of the theory of multibody kinematics [15] requires that the $n \times n$ submatrix of $S$, formed by deleting the $S_0$ row, be nonsingular. Therefore, if any entire column $\delta_{1..n}^0$ becomes zero, the matrix $S$ must be split into two nonsingular partitions and treated separately. Physically, this case corresponds to a modular structure split in two. The two substructures then experience no constraint forces or torques from each other.

The incidence matrix describes only whether pairs of modules are connected, not the kinematic relations governing each joint. We must further specify the kinematics with the multibody spacecraft mechanism Jacobian $J$. $J$ is a function not only of the FPI connectivity parameters $\delta_{ij}^0$, but also of the particular geometry of each FPI. Flux-pinned interfaces can form joints because flux pinning constrains only those DOF aligned with nonzero magnetic field gradients. Thus, a cylindrically symmetric magnetic field source (such as a pure dipole, solenoid, or cylindrical permanent magnet) flux pinned to a superconductor is free to rotate about the axis of symmetry in its field. Figure 1 illustrates three possible joints based on this principle. Other joints are possible, derived from any magnetic field distribution with one or more coordinates along which the field gradient is zero. This requirement on magnetic field distribution suggests one way to lock and release selected DOF in a flux-pinned joint without disengaging the interface thermally: electromagnets may simply toggle on and off to introduce or remove a field gradient. Other joints may not be affected by the changing field if they are beyond the minimum range for flux pinning [13].

### III. Example Applications

Three simple examples illustrate some capabilities of spacecraft reconfiguration via kinematic mechanisms. The first two (Fig. 2) demonstrate how appropriate selection of FPI degrees of freedom may change the physical structure of a modular system. In these cases, the initial configuration consists of a series of square cross section modules arranged in a line (Fig. 2, top and bottom). A walking reconfiguration moves a module from one end of the line to the other, depicted schematically in the top half of Fig. 2. The target module (with darker shading in the figure) turns its fixed FPI into a hinge and “walks” down the line by successively switching the interface that forms the hinge. When the target module changes its interface from a fixed one to a hinge, as it does between stages i–ii, it alters its Jacobian. Similarly, changing the location of the hinge between stages iii–iv and vi–vii involves a new choice of FPI parameters $\delta_{ij}^0$, altering $S$. The remaining modules in the system need not change their kinematic properties. Although this example involves only three modules, it can easily be generalized to walk a module along an arbitrarily long (or arbitrarily shaped) chain. This idea may be extended to the creation of related machines, such as gears and screws.

A more complex reconfiguration of a three-module chain appears in the bottom row of Fig. 2. This is a Jacob’s ladder reconfiguration, which does not change the order of modules in the chain but rotates each 180 deg about an axis perpendicular to the chain. It involves more control over the flux-pinned joints in the formation, with both $J$ and $S$ changing simultaneously at some stage in the process and multiple FPIs concurrently releasing a DOF. Reconfiguration begins with one module on the end of the chain hinging as in a walking reconfiguration. This module then becomes the pivot for reconfiguration (ii). The remaining modules rotate such that a new module takes the pivot position (iii–iv). Again, this reconfiguration maneuver generalizes to systems with $n > 3$. The last module in the chain hinges to restore the original shape of the system, with each module individually rotated about its center (vi–vii). Momentum actuators could drive either of the reconfiguration processes in Fig. 2.
The third example is a demonstration of the noncontacting hinge concept with 3 DOF mock-up modules on an air table. The FPI on the demonstration modules of Fig. 3 has a simple design: a YBCO superconductor immersed in a small nitrogen bath is on the corner of one module and a cylindrical NdFeB rare-Earth permanent magnet sits on the adjacent corner of a second module. In addition, the second module incorporates a simple momentum wheel activated by remote control. The thin, cylindrical magnet has a high magnetic...
field magnitude and field gradient in the vertical and horizontal translation directions, which provide high FPI stiffness (tens of newtons per meter) between the “magnet module” and “superconductor module.” However, the axially symmetric field allows demonstrations of free rotation about the magnet’s dipole axis. When the momentum wheel spins up or down, its torque causes the magnet module to rotate about the noncontacting joint axis. Both demonstration modules remain stiffly connected in the other two relative degrees of freedom. (Note that a counterweight restricts movement of the superconductor module, so its motion due to forces and torques transmitted through the FPI is less apparent than the motion of the magnet module.) Because the kinematics and momentum actuator govern this reconfiguration procedure, the problems of plume impingement, relative orbital dynamics, and other issues, which may affect spacecraft reconfigurations consisting of sequences of docking and undocking maneuvers, are not present in this system. This mock-up demonstrates both the action-at-a-distance stiffness of flux pinning and an FPI’s ability to reconfigure by forming a noncontacting revolute joint, a building block for many kinematic mechanisms, including those in the previous two examples.

IV. Conclusions

Reconfiguration of fractionated spacecraft is a challenging dynamics and control problem. It is possible that these challenges can be partly or fully addressed by instead treating the problem of spacecraft reconfiguration as a kinematic one. Selection of the appropriate kinematic constraints adds determinism and robustness to modular systems. The extensive theory of multibody kinematics and kinematics of machines can then apply to spacecraft reconfiguration applications. The need for active control and actuation during reconfiguration maneuvers decreases if the system kinematics are prescribed in such a way.

We view the flux-pinched interface as an enabling technology for such reconfigurable kinematic systems. FPIs are capable of locking and freeing joints between spacecraft modules (altering the spacecraft Jacobian), as well as latching onto and releasing the modules entirely (changing the incidence matrix of the multibody system). We have described two simple ways in which FPIs enable the formation of mechanisms to reconfigure a modular space system. In addition, we have demonstrated a simple kinematic mechanism incorporating an FPI on an air table. Future work in this area will concentrate on the development of suitable flux-pinched interfaces for the formation of kinematic mechanisms and on maneuver strategies for such mechanisms in spacecraft reconfiguration. However, the prospect of treating reconfigurable, modular spacecraft systems as kinematic mechanisms has more general application than to systems mated with flux pinning.

References


