Safe On-Orbit Servicing of Non-Rigid Satellites

Bennett Russell*† Ruben McWilliams*, Nathan Wolfe*, Longsen Gao*, Rafael Fierro*
* Electrical and Computer Engineering, University of New Mexico, Albuquerque, United States
† bennettrussell@unm.edu

I. Introduction

Safe autonomous on-orbit servicing (OOS) requires tightly integrated modeling, control, and validation to manipulate noncooperative, partially known spacecraft while respecting stringent safety and load constraints. This report distills ongoing research efforts that unify: (i) a model-based, safety-critical framework for *Safe Decentralized Adaptive Operations* (SDAO) on non-rigid clients and (ii) a multi-robot emulation platform that reproduces salient contact and actuation phenomena of OOS in the laboratory. Together, these efforts address two canonical operations: (1) interactive dislodging of a jammed, compliant appendage with uncertain stiffness/damping and (2) transportation and capture of a free-floating non-rigid module. We summarize problem settings, dynamics, control architectures, and the enabling testbed, focusing on independently verifiable statements and cohesive interfaces between modeling and experimentation [1], [2].

II. Problem Formulation and System Overview

Agents. A *Space Servicing Unit* (SSU) is a free-flying service element with 6-DoF actuation that can apply a 6-DoF wrench (force/torque) to its environment. Two classes are considered: an agile low-wrench *A-SSU* and a high-wrench, slower *B-SSU*. A client consists of a rigid base (*Link-1*) and a hinged, compliant appendage (*Link-2*)—representative of a partially deployed solar panel—with an underpowered hybrid hinge that exhibits spring, damping, and friction effects. Physical parameters (mass, inertia, local geometry, hinge stiffness/damping, friction) are partially unknown to the servicer.

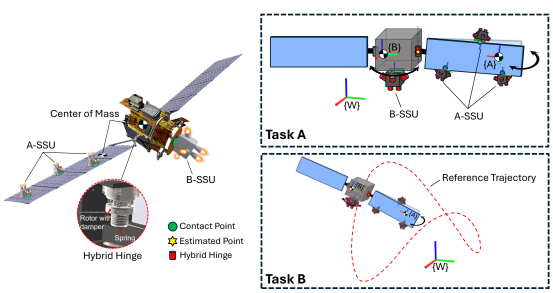

Fig. 1. Depiction of SDAO intended configuration

This material is based on research sponsored by Air Force Research Laboratory (AFRL) under agreements FA9453-18- 2-0022 and FA9550-22-1-0093. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Air Force.

Tasks. *Task 1: Dislodging with unknown stiffness.* The goal is to command a safe reference motion for the compliant appendage—specified by desired attitude $\mathbf{R}_d \in SO(3)$ and angular velocity $\boldsymbol{\omega}_d \in \mathbb{R}^3$—while respecting structural and actuation limits despite parametric uncertainty. *Task 2: Transportation of a non-rigid client.* The goal is reference tracking in $SE(3)$ for the combined module, $\mathbf{q}_d(t) = [\mathbf{p}_d^\top, \boldsymbol{\theta}_d^\top]^\top$, in the presence of uncertain mass–inertia and configuration-dependent Coriolis/centripetal effects. Both tasks may be carried out by robot arms attached to a carrier or by multiple SSUs applying coordinated wrenches [1].

A. Composite Dynamics of a Non-Rigid Client

Let $\mathbf{q} = [\mathbf{p}^\top, \boldsymbol{\theta}^\top]^\top \in \mathbb{R}^6$ denote task-space position/orientation coordinates (with $\boldsymbol{\theta}$ any minimal attitude coordinate derived from unit quaternions to avoid singularities), and let $\boldsymbol{\theta}_*$ be the *relative* angle across the hybrid hinge (i.e., the orientation of *Link-2* relative to *Link-1*). The client's composite wrench–motion relation in task space is written as

$$\mathbf{w}_\Sigma = \mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{D}_h\,\dot{\boldsymbol{\theta}}_* + \mathbf{K}_h\,\boldsymbol{\theta}_* + \mathbf{F}_f, \quad (1)$$

where $\mathbf{M}$ is positive-definite; $\mathbf{C}$ captures Coriolis/centripetal effects; $\mathbf{K}_h = \mathrm{diag}(k_x, k_y, k_z)$ and $\mathbf{D}_h = \mathrm{diag}(\xi_x, \xi_y, \xi_z)$ represent hinge stiffness and damping acting only on the relative rotational subspace; and $\mathbf{F}_f$ models Coulomb-like hinge friction engaged for $\dot{\boldsymbol{\theta}}_* \neq \mathbf{0}$. External interaction is expressed via grasp maps:

$$\mathbf{w}_\Sigma = \sum_{i=0}^{N} \mathbf{G}_i(\mathbf{q}, \bar{\mathbf{d}}_i)\,\mathbf{w}_i, \quad (2)$$

where $\mathbf{w}_i$ is the wrench applied at contact i (robot end-effector or SSU) and $\mathbf{G}_i$ maps that local wrench to the client's task-space wrench based on the contact pose $\bar{\mathbf{d}}_i$. The base and appendage dynamics appear additively in (1) through $\mathbf{M}$ and $\mathbf{C}$; hinge terms $(\mathbf{K}_h, \mathbf{D}_h, \mathbf{F}_f)$ couple the links through $\boldsymbol{\theta}_*$ [1]. Unknowns include link masses, composite inertia about an off-COM point, and hinge parameters.

III. Safety-Critical SDAO Control in SE(3)

SDAO combines decentralized adaptive control with *control barrier functions* (CBFs) to ensure constraint satisfaction while tracking reference trajectories under uncertainty. For each actuator group (e.g., arms or SSUs) a nominal adaptive controller $\mathbf{u}_{\text{nom}}$ compensates unknown inertial and hinge parameters in (1), while CBF constraints modulate the commanded wrench/velocity to enforce state/input safety sets:

$$\mathbf{u}^{\star} = \arg\min_{\mathbf{u}} \ \|\mathbf{u} - \mathbf{u}_{\text{nom}}\|^2 \quad \text{s.t.} \ \ \dot{h}(\mathbf{x}) + \alpha\, h(\mathbf{x}) \geq 0, \ \mathbf{u} \in \mathcal{U}, \tag{3}$$

with $h(\mathbf{x})$ encoding barrier functions for, e.g., joint/attitude limits, contact forces, hinge load envelopes, and collision avoidance; $\alpha > 0$; and $\mathcal{U}$ actuator bounds. For dislodging, a reference $(\mathbf{R}_d, \boldsymbol{\omega}_d)$ is chosen to respect hinge deflection and rate limits; for transportation, a pose–twist reference in $SE(3)$ is tracked while limiting contact forces and structural loads.

IV. Emulation Platform and Controller Designs

A. Hardware and Software Architecture

A dual-gantry, multi-robot platform emulates OOS interactions with high repeatability and instrumentation. Two 6-DoF industrial arms (UR5e and UR10e) are mounted on independent carriages along a 5-m rail driven by a Vention MachineMotion v2 controller, forming two 7-axis (prismatic+6R) manipulators; an optional Barrett WAM can be mounted interchangeably. A 16-camera Vicon system provides global ground truth alongside native arm encoders and 6-axis F/T sensing. Safety is enforced with integrated light curtains and a safety controller that interlocks the gantry and robot controllers. Software is built on ROS 2 with the `Universal_Robots_ROS2_Driver` and a custom Vention driver (`unm_ros2_vention`). A modular satellite emulator constructed from T-slot aluminum accepts swappable payloads, including a *hybrid hinge* with adjustable springs, a torque limiter, and a cammed "stiction track" that creates multi-stable resistance profiles representative of jammed appendages [2]. Although true microgravity is not present, in-the-loop emulation maps measured contact wrenches to target dynamics to approximate free-float behaviors where needed.

Fig. 2. Image of emulation testbed

B. Stiction-Aware Dislodging via POMDP

To address partial observability and non-linear friction in the hybrid hinge, a belief-space controller is formulated as a partially observable Markov decision process (POMDP). States include kinematics and a discrete "stuck/free" indicator; actions are end-effector forces/torques; observations are noisy velocity and contact/friction proxies. Beliefs are updated using *Bayes' rule* (standard POMDP filtering), and a multi-objective stage cost balances time, work, and risk,

$$c(b, a) = Q_t(b, a) + \alpha Q_w(b, a) + \beta Q_r(b, a),$$

with a safe action set $\mathcal{A}_{\text{safe}}(b) = \{a \mid Q_r(b, a) \leq p_{\max} - \varepsilon\}$. Contact is modeled by a linear spring–damper normal law and Coulomb tangential friction,

The policy determines when to apply impulses sufficient to exit stiction versus when to modulate forces to avoid over-excitation; on the testbed, additional safety is enforced by robot-side limits and monitors.

C. Contact-Based Detumbling and Capture

For non-destructive detumbling, two end-effectors alternately execute short-duration contacts whose lines of action pass through the target's centerline, trading angular momentum without large sustained forces. With contact point P and target COM A, the wrench satisfies $F_A = F_P$ and $\boldsymbol{\tau}_A = \mathbf{r}_{AP} \times F_P$. Normal–tangential contact is as above. The end-effector intercept point Q is the intersection of the target's predicted trajectory line $\ell_t : y = a_t x + b_t$ and the end-effector line $\ell_h : y = a_h x + b_h$,

$$Q = \left[\frac{b_h - b_t}{a_t - a_h}, \ \frac{a_t b_h - a_h b_t}{a_t - a_h} \right]^{\top}, \tag{4}$$

with a timing condition that the end-effector reaches Q no later than the target. A speed command that enforces this is

$$\left\|\dot{\mathbf{v}}_h^d\right\| \ = \ k_h \frac{\|Q - \mathbf{p}_h\|}{\|Q - \mathbf{x}_p\|} \|\mathbf{v}_t\|. \tag{5}$$

The desired task-space twist is mapped to joint rates using the *Jacobian pseudoinverse*, rather than reproducing the well-known formula explicitly. Safety during repeated impacts is enforced by limits on contact force envelopes, arm joint/rail motion, and keep-out zones implemented in the testbed controllers.

V. Discussion and Limitations

The SDAO model (1) captures rigid–flexible coupling via a hinge with uncertain parameters while admitting grasp-superposition (2) for multi-contact operations. Decentralized adaptive control addresses parametric uncertainty without centralized inversion of full-body dynamics, and CBFs provide formal safety certificates for hinge deflection/rate, contact wrench cones, and actuator limits. The emulation platform exposes realistic sensing/latency and contact nonlinearities (e.g., multi-stable stiction) not easily captured in pure simulation. The POMDP formulation handles partial observability and explicitly trades time/energy/risk; conceptually complementing SDAO. Practical limitations include residual model mismatch in in-the-loop microgravity emulation, sensitivity of impact timing to sensing latency, and dependence of frictional transients on surface condition.

References

[1] L. Gao, C. Danielson, B. Russell, and R. Fierro, "SDAO: Safe Decentralized Adaptive Operations for Non-rigid Satellite," ongoing research manuscript, Univ. of New Mexico and AFRL.

[2] B. Russell, N. Wolfe, G. Gutow, L. R. Garcia Carrillo, C. Danielson, and R. Fierro, "A Multi-Robot Experimental Platform for Emulating Autonomous On-Orbit Servicing," ongoing research manuscript, Univ. of New Mexico, Carnegie Mellon Univ., and AFRL. Accepted in AIAA Scitech 2026