LEARNING-AUGMENTED OPTIMAL DEPLOYMENT OF NET FOR RELIABLE CAPTURE OF SPACE DEBRIS. R. K. Shah[1], C. Zeng[1], S. Chowdhury[1], and E. M. Botta[1], [1]Department of Mechanical and Aerospace Engineering, University at Buffalo, 240 Bell Hall, Buffalo, NY, 14260, USA.

Introduction: Tether-nets have been proposed to capture space debris, so as to decrease the risk of collisions with operational spacecraft and ensure the sustainability of orbit exploitation. Tether-nets are designed to be ejected from a chaser spacecraft in close proximity with a target, to envelop the latter and entangle or close around it, and to maintain the link to allow for its tugging to a disposal orbit (see Figure 1). Key to the feasibility of this capture mechanism in space is the reliability and safety of the process, especially considering that the same net cannot be deployed more than once in a given space flight.

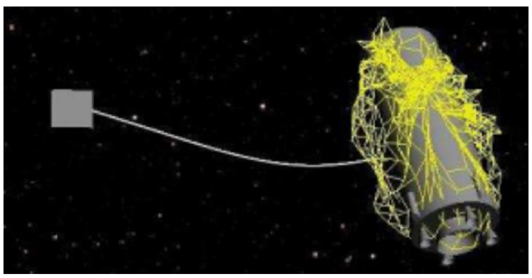

Figure 1: Illustration of tether-net capture of debris.

Several simulations of deployment and capture dynamics have been performed recently. Most existing works have assumed the net system to be designed for successful capture of a specific target, and the launch conditions to be ideal, symmetric, and centered with respect to the target. In contrast, Botta et al. [1,2], Salvi [3], and more recently Endo et al. [4] have studied the robustness of capture in different launch conditions to some extent. However very little work has gone into studying the effects of uncertainty, e.g., attributed to lack of knowledge of the net material or imperfect state estimation of the debris, on the reliability of the capture process. Specifically, there is a critical need to identify systematic computational methods to control the net deployment and entanglement process in a manner that satisfies pertinent constraints under uncertainties.

The purpose of the present work is to adopt an optimization under uncertainty approach to regulate the deployment design and process, with the objective to guarantee successful capture of debris. The focus of this work is mainly on the deployment phase. Since the simulation of capture is computationally expensive, the optimization process could become intractable, especially when uncertainties are to be computed internally. Thus, we propose to leverage machine learning tools, mainly global function approximators, to build surrogate models, which can then significantly reduce the cost of optimization (compared to performing a direct simulation-based optimization).

Methodology: The deployment dynamics is first formulated as an optimization problem. Design variables are relative to the capture system (e.g., the mass of the corner masses and the geometry of the net) and the net ejection conditions (e.g., relative position and orientation of the chaser with respect to the target, magnitude and direction of the velocity of corner masses ejection). Cost functions and constraints are defined so as to achieve a deployment of the net sufficient to envelop the target, for an adequate time, and while ensuring that capture will occur at a safe distance. We explore both gradient based (mainly sequential quadratic programming) and surrogate based gradient-free (with robust Particle Swarm Optimization [5]) algorithms to perform the optimization.

Optimization of the deployment is then performed for a specific capture scenario, with set target geometry and initial conditions. The scenario is simulated with an existing tool, in which the net is modeled with the standard lumped-parameter approach, the chaser is a rigid body, and the main tether is modeled as a series of slender rigid bodies and prismatic joints [6]. To demonstrate the effect of uncertainty, we add Gaussian noise to both the configuration of the net and the assumed state of the debris. Probabilistic constraints are then modeled to perform reliability-based optimization. A set of simulations are sampled and used to train the learning (aka surrogate) models, mainly Kriging and neural network models of the quantities of interest as functions of the design variables and uncertain parameters. Thereafter, the surrogate models are used to perform the optimization. The optimum solutions are to be validated with the original simulation, and compared with baselines from existing literature. Different numerical experiments are performed to analyze the impact of parameter and model uncertainties on the reliability of the ensuing optimal solutions.

References: [1] Botta, E. M., et al. (2017) *Acta Astronaut*. 140, 554-564. [2] Botta, E. M., et al. (2016) "Evaluation of net capture of space debris in multiple mission scenarios." *26th AAS/AIAA Space Flight Mechanics Meeting*, Napa, CA. [3] Salvi, S. "Flexible devices for active space debris removal: the net simulation tool." (2014), Thesis, Politecnico di Milano. [4] Endo, Y., et al. (2020) *Adv. Space Res.* 66.2, 450-461. [5] Ghassemi, P. et al. (2020) *Struct. Multidiscip. O.*, https://doi.org/10.1007/s00158-020-02592-6. [6] Botta, E. M., et al. (2019) *Acta Astronaut*. 155, 448-461.