Literature Review

Scott Plantenga

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1 Introduction

On-orbit satellite servicing is critical to maximizing space utilization and sustainability. Considering a future involving large, complex space structures operating far beyond Low Earth Orbit, reliance on astronauts or anchored robotic arms for servicing of such space structures is impractical. Substantial literature exists investigating the dynamics, control, and design of robotic servicing missions that utilize a single satellite to approach and service a target. This motivates the present research to investigate a fleet of small robotic satellites performing operations for a central space structure such as a large, complex space station or space telescope. This investigation employs a model-based systems engineering approach, with special attention to the modelling and simulation of the dynamics and control of the servicing fleet. Thus, presented here is a review of pertinent literature on robotic servicing, model-based systems engineering, and relative motion dynamics and control.

2 Robotic Satellite Servicing

Satellite servicing performed via human Extravehicular Activity (EVA) has been demonstrated with the Hubble Space Telescope (HST) and the International Space Station (ISS) [1]. However, utilizing human EVAs for all servicing operations is not cost effective nor universally applicable [2]. As a means for servicing, using human EVAs requires transport of astronauts to and from the target satellite, a massive expense for target satellites outside of Low Earth Orbit (LEO). Robotic servicing satellites are necessary when the target is inaccessible to humans, such as in Geostationary Earth Orbit (GEO) or at a Sun-Earth Lagrange point such as L1 or L2 [1],[2]. Satellites placed in these distant orbits tend to be large, expensive platforms with advanced payloads and thus represent a strong candidate for on-orbit servicing [2]. Robotic servicing satellites also remove the risk to human life and allow for specialized operations exceeding the dexterity, strength, positioning accuracy, and/or speed of a human operating from within a spacesuit [1].

2.1 Previous Robotic Servicing Missions

The technology for robotic on-orbit servicing has been demonstrated through both government and commercial missions [1],[3]. For example, the United States Air Force Research Laboratory (AFRL) developed the Experimental

Spacecraft System Number 11 (XSS-11) to demonstrate the capability for safe, autonomous rendezvous and proximity operations [1]. The XSS-11 was successfully operated in LEO from 2005 to 2006 to demonstrate the capability to autonomously perform safe and reliable rendezvous and proximity operations with a non-cooperative resident space object [1]. In 2007, the Orbital Express mission, sponsored by the United States Defense Advanced Research Projects Agency (DARPA), provided the first demonstration of successful end-to-end robotic satellite servicing activities [1]. The mission involved two specially designed satellites to demonstrate this technology [1]. During the mission, the chaser satellite successfully performed autonomous docking with the target satellite and demonstrated servicing activities including fuel transfer, insertion of battery, and changeout of a flight computer [1]. More recently, Northrop Grumman's Mission Extension Vehicles (MEV-1 and MEV-2) demonstrated the capability for autonomous rendezvous, docking, and servicing in GEO [3]. In February 2020, MEV-1 performed autonomous rendezvous and docking with a functioning but not transmitting communication satellite residing in the GEO graveyard [3]. The communication satellite was still functional, but due to low fuel was moved to the GEO graveyard for decommission [3]. MEV-1 now provides attitude and orbital control to the fuel-deficient communication satellite and has maneuvered it back to the operational GEO belt, allowing for profitable operation of the communication satellite to resume [3]. In April 2021, MEV-2 performed a similar autonomous rendezvous and docking, this time with a communication satellite that was actively transmitting from the GEO belt [3]. MEV-2 demonstrated another successful autonomous rendezvous and docking in GEO, and further demonstrated that this can be done with an active satellite without interrupting the satellites function [3].

2.2 Current Development of Robotic Servicing Missions

In addition to the ongoing MEV missions, there is ongoing development of government-sponsored servicing missions such as the OSAM-1 and RSGS programs [4],[5]. Part of NASA's Exploration and In-space Services (NExIS) efforts is the development of the On-orbit Servicing, Assembly, and Manufacturing 1 satellite (OSAM-1), a robotic system designed to perform a refueling, assembly, and manufacturing demonstration with a launch scheduled for 2024 [4]. The mission for OSAM-1 is to rendezvous with, grasp, refuel, and relocate a target satellite to extend its life [4]. OSAM-1 will also utilize its Space Infrastructure Dexterous Robot (SPIDER) to assemble seven elements to form a functional communications antenna and manufacture a 10-meter lightweight composite beam [4]. Additionally, DARPA is executing the Robotic Servicing of Geosynchronous Satellites (RSGS) program to develop technologies that will enable cooperative inspection and servicing in GEO, and demonstrate those technologies on orbit within the next five years [5]. The goals of the RSGS program are to demonstrate that robotic servicing vehicles can perform safe, reliable, useful, and efficient operations on operational satellites in or near GEO; and to support the development of a servicing satellite with sufficient propellant and payload robustness to enable dozens of servicing missions across several years [5].

2.3 Servicing and Assembly of Large Space Structures

As discussed previously, the Hubble Space Telescope (HST) was successfully serviced five times from 1993 to 2009 with crewed missions to bring astronauts to HST and perform servicing operations [1],[6]. HST was designed to allow for astronauts to perform repairs, replace parts, and update its technology with new instruments [6]. While this demonstrated the ability to service a large, complex space structure, it was performed entirely with human EVAs and cost \$1-2 billion for each servicing mission [1]. The James Webb Space Telescope (JWST), the nearly \$10 billion successor to HST with a launch planned for December 2021, is not designed to be serviceable [7]. NASA cites the design redundancy, extensive seven year integration and test program, and unreachable orbit about the Sun-Earth second Lagrange point (L2) for this decision [7].

The assembly and servicing of the ISS is performed with a combination of human EVA and robotic activity [8]. The Mobile Servicing System (MSS) is the robotics suite on the ISS that performs robotic assembly, maintenance, and resupply activities [8]. The MSS consists of three components: the Space

Station Remote Manipulator System (SSRMS, also known as Canadarm2), the Special Purpose Dexterous Manipulator (SPDM, also known as Dextre), and the Mobile Base System (MBS) [8]. The MBS can slide along truss rails and provides a storage area for EVAs and anchor points for the SSRMS and the SPDM [8],[9]. The SSRMS (Canadarm2) is a large, 7-degrees-of-freedom robotic arm that was used extensively for the assembly of the ISS and currently performs servicing for the ISS and grappling of visiting satellites [8],[10]. The SPDM (Dextre) is a smaller robotic system with dual-arms, precision handling capability, lights, video equipment, a tool platform, and four tool holders to perform servicing and reduce the need for EVAs [8],[11]. Dextre can be attached to the MBS directly, or to the end of the Canadarm2 for even greater mobility [11]. The purpose of the MSS is to limit the amount of human EVAs required, however it is still common for human EVAs to be performed for certain operations [8].

The China Manned Space Agency (CMSA) is currently assembling their own space station, called Tiangong, with a similar combination of human EVA and robotic activity [12]. Tiangong assembly began in May 2021 with the launch of the first module, Tianhe, and subsequent visiting cargo and crew satellites have performed autonomous rendezvous and docking with Tianhe [12]. The crewed missions aid in the set-up of Tianhe and the external robotic arm that will be used to help position the two research modules planned for launch in 2022 and assist astronauts during spacewalks [12].

Once completed, Tiangong will be joined by a large space telescope that will share Tiangong's orbit and be able to dock for the possibility of repairs, maintenance, and upgrades [12].

As part of NASA's Artemis mission to return humans to the surface of the Moon, the Gateway will be an outpost in permanent orbit about the Moon that provides infrastructure for a long-term human return to the lunar surface, as well as a staging point for deep space exploration [13]. The Canadian Space Agency (CSA), the developers of Canadarm2, has an agreement with NASA to provide a similar advanced external robotic arm called Canadarm3 for Gateway [13]. Canadarm3 will be designed to maintain, repair, berth, and inspect visiting vehicles, relocate Gateway modules, visually inspect Gateway, install science payloads, and assist astronauts during EVAs and experiments [13]. Canadarm3 is designed to work autonomously, but could also be operated by flight controllers on the ground or Gateway crew during EVAs [13].

3 Model-Based Systems Engineering Methodologies

The International Council on Systems Engineering (INCOSE) defines Model-Based Systems Engineering (MBSE) as the "formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [14]. System relationship models are developed to show relationships between system functions, requirements, developers, and users [14]. These models support three key aspects of systems engineering: System Architecture or Functional Flows, System Requirements Traceability, and System/Organizational Process Flows [14]. Several methodologies for MBSE have been developed and surveyed [15].

3.1 SysML

In practice, most MBSE methodologies make use of System Markup Language (SysML) [14],[15]. SysML is a visual modelling language developed by the Open Modeling Group as an extension of the Unified Modeling Language (UML) to further support the specification, analysis, design, verification, and validation of complex systems [16]. Individual models are created as diagrams to represent elements of the system and relationships between elements [16]. Various diagram types exist in SysML to model the system structure, system behavior, requirements for these structures and behaviors, and parametric relationships between element parameters and their behavior [16].

3.2 JPL State Analysis

Several methodologies are commercially available, however some are made publicly available, such as the State Analysis (SA) methodology developed by JPL [15]. SA is an MBSE methodology with special focus on state and goal-based control [15]. States are defined in SA as a broader extension beyond the position/attitude classical control theory definition to also include system component modes, available resources, and all other physical or logical parameters that can be used to represent a momentary condition of the evolving system [15]. The states and models together are meant to define everything needed to operate the system, predict future states, control towards a desired state, and assess system performance [15]. SA is primarily used for state-based behavioral modelling, state-based software design, and goal-directed operations engineering [15]. This state-based approach to MBSE is also utilized in the Horizon Simulation Framework, which is the MBSE framework utilized for the present research.

3.3 Horizon Simulation Framework

The Horizon Simulation Framework (HSF) is a modelling and simulation framework for verification of system level requirements, with an emphasis on state representations, modularity, flexibility, and event scheduling [17],[18]. HSF consists of two major modules with very limited interaction, the main scheduling algorithm and the system model [17]. This fundamental modularity was implemented to allow independent development of both the scheduling algorithm and the system model, allowing for much greater user flexibility [17]. Furthermore, the system model is composed of modular subsystems with explicitly defined interactions [17]. Users create a model of their system in HSF with specifications of these subsystems and their interactions/dependencies with one another [17],[18]. Users specify simulation parameters, such as initial states and timing parameters, that are used to create a Day-in-the-Life (DITL) scenario to investigate the system model [18]. System-level requirements are evaluated by developing numerous DITL schedules and comparing the events executed in each schedule [18]. Subsystem requirements are built into the simulation in the form of constraints, which compare the value of state variables to some limiting range [18]. The DITL simulation seeks to be exhaustive through a breadth-first-search scheduling algorithm to test all possible scenarios that can be executed by the system to accumulate a large amount of data about successful system use cases and system failure points [18]. HSF was originally built upon C++ and SysML, but has since been adapted to utilize XML input/output files, a C# codebase, and Python scripting to define subsystem models [18].

HSF has previously been utilized for modelling and analysis of guidance, navigation, and control systems by Maclean [19], Frye [20], and Johnson [21]. Maclean's research involved modelling an active control system for a sounding rocket based on linear-quadratic regulator (LQR) control theory [19]. Frye's research involved modelling the performance of a swarm of UAV's through the use of digital pheromones, pheromone mapping, and an LQR set-point controller to maneuver the pheromone map [20]. Johnson's research involved modelling an astronomy CubeSat, with special focus on the attitude dynamics and control [21]. This work demonstrates the applicability of scripted models in HSF and establishes a baseline for my development of dynamics and control modelling with HSF.

A major developmental goal of the on-going HSF project is to foster an open-source community to further develop the models, libraries, and applications of HSF. –some well-written stuff from Jack Balfour's thesis or his references on what makes a good user community, likely along the lines of making standards and unit tests – Previous work has been done to develop unit tests and code standardization for the main scheduling algorithm of HSF [22]. Part of the present research is to develop the same level of standardization and unit testing for the development of Python subsystem models and the library of utility functions.

4 Dynamics and Control Modelling for Servicing Satellites

The dynamics of interest for the modelling and simulation of a fleet of servicing satellites are relative orbital motion and rigid body attitude dynamics. Relative orbital motion is controlled through mass-expulsion thrusters, which can be modelled as impulsive changes in velocity or accelerations over time [23]. Attitude is controlled through some combination of external torques and momentum-exchange devices (MEDs) [23],[24]. The pertinent literature on the modelling and control of these dynamics is discussed in the following sections.

4.1 Relative Orbital Motion

Orbital motion of any Earth orbiting satellite is governed by a dominant 2-body gravitational attraction towards the Earth, several disturbance or perturbation accelerations arising from various phenomena, and control forces [23]. For an assumed circular target orbit and close spacing between target and chaser, the relative motion can be described with the Clohessy-Wiltshire (CW) equations, a famous set of linear constant coefficient differential equations commonly presented in astrodynamics textbooks [25],[26]. The solution to these equations can be expressed in a simple set of matrix equations, referred to as the Clohessy-Wiltshire or CW matrices [25],[26]. Furthermore, simple inversion of these matrix equations yields a solution for impulsive transfer trajectories. For a two-impulse maneuver with known start/end states and transfer time, the transfer trajectory and required delta-V vectors for the maneuver can be solved for with another set of matrix equations [25].

The relative orbital motion can also be analyzed for an unperturbed elliptical target orbit and close-by chaser through linearized equations of relative motion (LERM) and time-varying transformations to apply the CW equations to elliptical target orbits [27]. The LERM are the linear but time-varying differential equations that emerge from 2-body orbital motion and the assumption that there is a small separation between the chaser and target [27]. The analytical solutions to these differential equations are not as simple as the CW equations and are referred to as the Tschauner-Hempel (TH) equations [27]. The time-varying transformations arise from the Virtual-Chief (VC) and Virtual-Time (VT) methods [27]. In the Virtual-Chief method, a fictitious/virtual satellite with zero eccentricity is used as the chief (target) satellite for the CW equations, with both actual chaser and target satellites acting as chasers in this Virtual-Chief frame [27]. The relative motion is then defined by matrix equations representing the difference between the actual chaser and target states [27]. In the Virtual-Time method, the time-varying behavior due to the eccentricity of the target orbit is captured by evaluating the CW equations at a virtual time to represent how the solutions follow the same trajectory paths but different motion along these paths [27]. The CW, VC, VT, and TH methods were all compared to the true nonlinear solution for six cases of closely spaced, elliptical orbits [27]. It was found that the VC and VT methods had considerably less error than the CW method and the TH method offered at least four orders of magnitude of improved accuracy [27].

The relative orbital motion can also be analyzed with perturbations through exploitation of Gauss' and Cowell's variational equations [28]. Work has been done to model the relative motion dynamics with the effects of primary gravitational (J2) and atmospheric drag perturbations, two effects with a deep influence on relative motion for LEO satellites [28]. A resulting linear time-varying solution can be obtained from assuming small separation between chaser and target, similar to the TH equations except for the inclusion of the J2 and drag perturbations [28]. Simulation results indicate that this linear time-varying perturbed solution yields more accurate results than the TH equations for chasers and targets in an inclined LEO [28].

4.2 Optimal Control of Relative Orbital Motion

To preserve fuel and execute operations quickly, relative orbital motion must be controlled with some degree of optimality. As noted, when considering the inverted CW matrix equations for a two-impulse maneuver with known start/end states, the only variable that dictates the transfer trajectory and the required delta-V is the transfer time [25]. There are many numerical optimization techniques available in textbooks to solve such constrained optimization problems [29],[30].

However, this would only be solving for an optimal two-impulse trajectory, without any consideration for the possibility of improved optimality with an increased number of impulses. For fuel-optimal impulsive control of a linear system, it has been shown that the optimal control solution requires at most as many impulses as there are specified final state variables

[31]. Thus, at most six impulses are required for optimal control of relative orbital motion governed by the CW equations. Solutions for a fixed time fuel-optimal transfer with two, three, or four impulses have been obtained [32],[33]. There has also been further study of optimal impulsive relative orbit control with consideration for J2 perturbation and elliptical orbits [34]. However, these works do not consider path constraints.

4.3 Attitude Dynamics and Control

Rigid body attitude dynamics have been well-studied and most equations are described in textbooks. Attitude motion subject to an external torque is described by a single vectorized differential equation known as Euler's equation [24]. Attitude control is achieved with either external torques or MEDs [23],[24]. Attitude dynamics controlled by MEDs have unique equations of motion for each set of MEDs used due to the various gyroscopic coupling effects that develop with each control actuation scheme [24],[35].

To preserve fuel, minimize power consumption, and execute operations quickly, attitude must be controlled with some degree of optimality. A well-studied optimal control approach is to utilize the Linear Quadratic Regulator (LQR) to determine optimal control gains for linear state-space dynamics with full-state feedback control [36]. An LQR attitude controller has previously been implemented in HSF to control small changes in attitude state for a small satellite [21]. There has also been various approaches to consider the non-linearity of the attitude dynamics and a time-optimal maneuver to control large changes in attitude state [37]. There has also been study of a variable structure control approach for a large slew maneuver [38].

Still in work: further discussion of HSF user community with citation to Jack Balfour's Thesis. More on the results/details of the multiple impulses in CW frame, more on the results/details from the papers on large slews and variable structure attitude control. There could also be a mention of cooperative control?

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