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Graphical Abstract

On the Guidance, Navigation and Control of In-orbit Space Robotic Missions: A Survey and Prospective Vision

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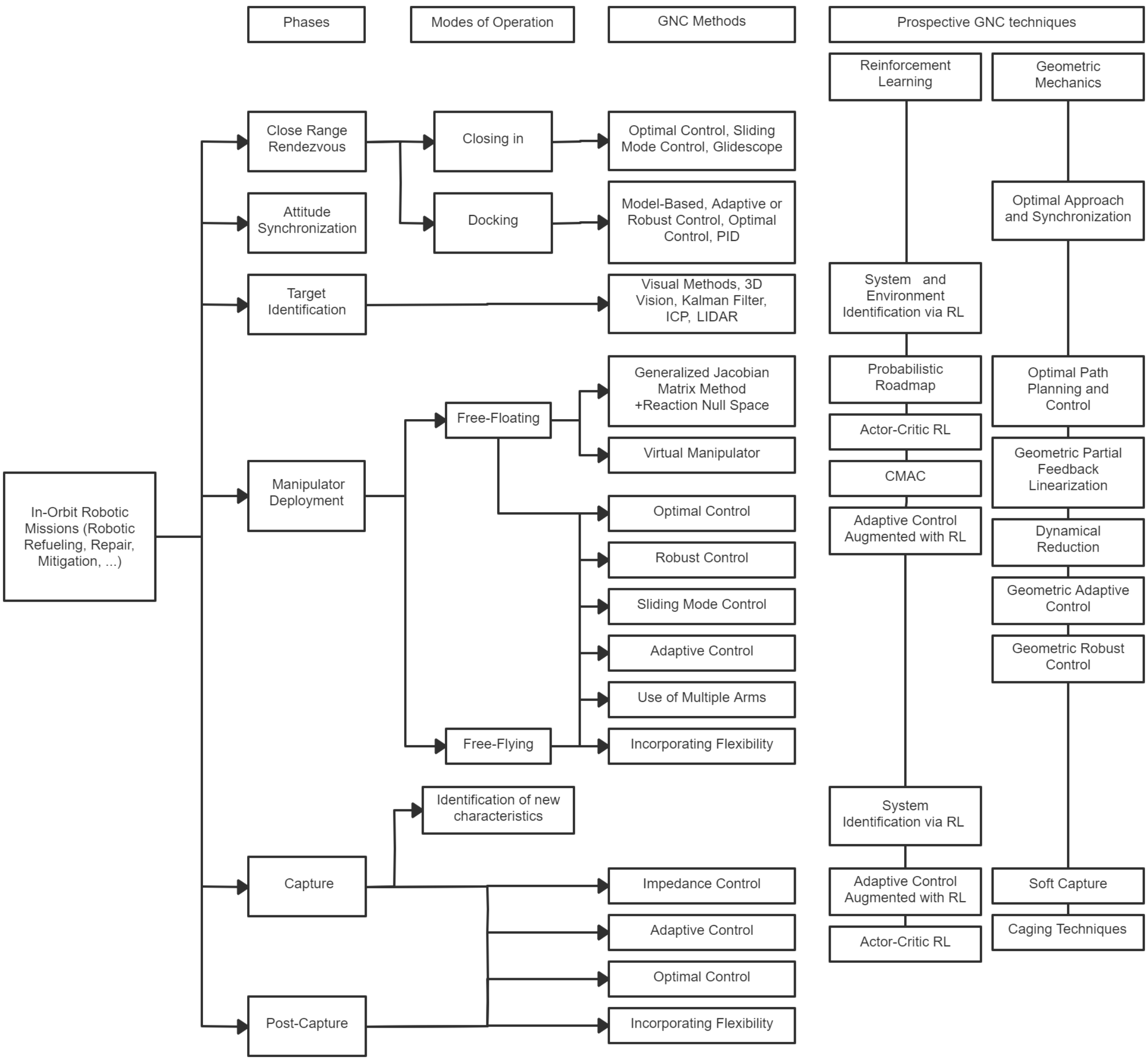

Highlights

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- The Guidance, Navigation and Control (GNC) methodologies used in various phases of in-orbit robotic missions performed by a spacecraft-manipulator system are reviewed.
- The GNC methodologies are presented in a unifying manner to provide a systematic comparison ground and list their advantages and disadvantages.
- Two new families of approaches are introduced that can noticeably improve GNC of spacecraft-manipulator systems.

On the Guidance, Navigation and Control of In-orbit Space Robotic Missions: A Survey and Prospective Vision⋆

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ABSTRACT

In the first part, this article presents an overview of Guidance, Navigation and Control (GNC) methodologies developed for space manipulators to perform in-orbit robotic missions, including but not limited to, on-orbit servicing, satellite/station assembly, probing extra-terrestrial objects and space debris mitigation. Some space mission concepts are briefly mentioned, for which space robotics is discussed to be among the most practical and universal solutions. Common phases of an in-orbit robotic mission are identified as: close-range rendezvous, attitude synchronization, target identification, manipulator deployment, capture, and if needed, post-capture maneuvers. Prominent GNC methodologies that are either proposed for or applicable to each phase are extensively reviewed. In the current article, the emphasis is placed on the study of GNC methodologies utilized in attitude synchronization, manipulator deployment, and capture phases, specially the ones reported for use in the two free-floating and free-flying operating regimes of space manipulators. Kinematics and dynamics of space manipulator systems are formulated to help unifying the presentation of the main ideas behind different GNC methodologies. Using a unified notation, comparison tables and discussions provided in this paper, researchers can compare various GNC approaches and contribute to the next-generation GNC systems for space robots. In addition, this survey aids technology users to learn about in-orbit robotic missions and choose appropriate GNC technologies for specific applications. In the second part of this paper, two families of emerging control schemes based upon reinforcement learning and geometric mechanics are introduced as promising research directions in the GNC of space robotic systems. The benefits of implementing these techniques to the GNC of in-orbit robotic missions are discussed. An exclusive study of environmental disturbances affecting space manipulators and their threat to long-term autonomy concludes this article.

1. Introduction

Recent major international space exploration programs aim to answer fundamental questions concerning human being, such as: “is there life beyond the Earth?", “what are the alternative sources of energy and material in the Solar system?", and “what are the cosmic threats to human existence?". Such programs have been mostly focused on visiting our closest celestial neighbors, i.e., the Moon and Mars, through manned or robotic missions. Manned missions to the Moon in the Apollo program are considered as a turning point in the history of the space industry. Moon’s geophysics was studied via placing ARTEMIS and Lunar Reconnaissance Orbiter in its orbit, or Lunokhod and Yutu on its surface. The Soviet Union sent the first landers to the Mars’ surface (Mars 2, 3 and 6) that were followed by many successful attempts by the National Aeronautics and Space Administration (NASA) under the Mars Exploration Program, e.g., Mars rovers such as Spirit, Opportunity, Sojourno, Curiosity, and landers including Viking and Pathfinder, to search for signs of life and examine the Mars’ environment for future manned missions. Aside from exploring the space, humans also use constellations of satellites in the Earth’s orbit to facilitate telecommunication and geo-spatial positioning (GPS, Glonass, and BaiDou), or to study the Earth from a perfect vantage point (Copernicus, Iridium), to observe the cosmos (James Webb and Kepler Telescopes), and to demonstrate and test our abilities for further exploration of the Solar system. In our most impressive collaborative achievement, many contributing states and companies including NASA, the Russian Space Agency (ROSCOSMOS), the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the Australian Space Agency contributed to building the International Space Station (ISS). Initially, the goal was to study the effects of micro-gravity and outer space environment on the human body and man-made technologies. In more ambitious attempts, Cassini was sent to Saturn and its moons to uncover the mysteries of their geophysics and atmosphere. ESA’s Rosetta mission was able to intercept an Asteroid via complex interplanetary orbital maneuvers and land on it. Finally, Voyager-1&2 spacecraft have been traveling to the edges of our Solar system, the farthest distance any man-made object has ever gone.

An integral part of any sustainable space exploration and exploitation program is advanced robotics. Space robotic systems not only serve as key enabling technologies to accomplish space missions, but they are also required for maintaining the existing space infrastructures to ensure continued services of satellite systems (e.g., telecommunication, Earth/cosmos observation, global navigation system, military surveillance, weather forecast, etc.) and building new

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ones beyond low Earth orbits. The role of space robotics is specifically crucial since they operate tirelessly and cost-effectively in the hostile and partially known outer space environment without endangering human lives.

Establishing a telemetry connection to orbital and deep-space crafts is a major concern. It is not always possible to teleoperate them from earth-based stations in real-time, due to inevitable communication delays. On the other hand, keeping a human operator in orbit for long stretches of time or at far distances from the Earth's surface is not logistically, financially and at times morally viable. Therefore, space missions (especially missions involving handling objects in the Earth's or other planets' orbits) greatly benefit from resilient and intelligent autonomous robotic systems that are capable of making local decisions. This has fuelled the boom of autonomous robotic systems for space exploration and exploitation, the most prominent of which are space manipulators[97]. In the 1980's several researchers and organizations started investigating the idea of incorporating robotic manipulators on-board spacecrafts for in orbit servicing tasks [212, 120]. Studies were performed on possible applications of teleoperated robots in space[26]. A robotic concept was developed in 1986 by NASA to move orbital replacement units from a space station to an orbital servicing vehicle in its vicinity[52].

Another major concern of players in the space sector was the potentially destructive effects of leaving out-of-service satellites unchecked in the Earth's orbits. Space debris threatens operational spacecraft and satellites by causing a cascading collision catastrophe, named the Kessler syndrome after Donald J. Kessler who first warned about this phenomenon in 1978 [161]. Researchers around the globe started proposing suitable methods for capturing, manipulating or disposing of these orbital objects. One of the mitigation methods is capturing debris with nets or dragging them with tethers. Among the developed approaches are the use of single or branching tethers[125], momentum exchange tethers[119], tether tugs[34, 35, 36], visco-elastic tethers[124], and electro-dynamic tethers[156]. Ion beams to push the debris out of orbit[48], capturing the debris via harpoons[283, 88], grappling systems[284], and drag augmentation devices[376] are examples of other debris mitigation approaches. Parallel to this effort, other researchers have been focused on servicing, refueling and repairing satellites in orbit, to keep old satellites in service. A servicer solution needs to dock with the target satellite, a task which was first experimented on a Japanese robotic satellite ETS-VII[403] (Engineering Test Satellite VII as shown in Figure 1[157]).

The recent growth in the interest in observing, studying, sampling and even mining asteroids has also raised opportunities for researchers to propose autonomous robotic systems for space capitalization. In Hayabusa and Hayabusa 2 missions, robotic asteroid samplers were successfully employed by Japanese Space Agency in the microgravity environment[155, 350, 397, 344]. The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx, Figure 2) is a NASA robotic mission to the near-Earth asteroid Bennu on a Touch-And-Go (TAG) trajectory to collect a sample via a robotic arm[211]. The near-Earth Asteroid Retrieval Mission (ARM) combines robotic and human exploration to capture a non-cooperative asteroid in deep space and transport it back to the Earth[53]. A non-cooperative target, rather than a cooperative target, is a space object that is not actively controlled to facilitate the docking and manipulation by a robotic spacecraft. Asteroids may also pose a threat to the life on the Earth. Planetary defense mechanisms using autonomous solutions for in-orbit manipulation or deflection of potentially destructive asteroids have become another major concern for the researchers in the field of space robotics. Some of these methods include: Ion beams that deflect the path of incoming asteroids[48], a massive gravity tractor (utilizing mutual gravitational pull to manipulate asteroid's course)[195], deflection via mirrors [373], solar light plumes[107] and controlled impact with object[372].

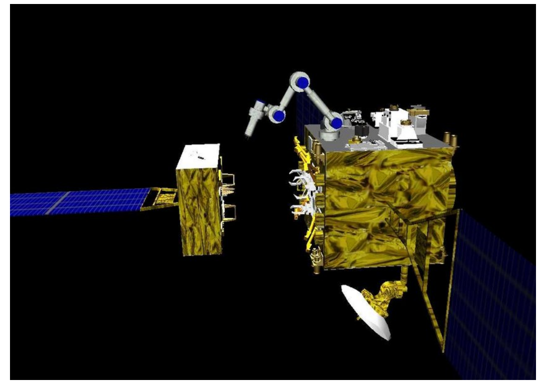

Figure 1: The first on-orbit experiment in the world on the Japanese satellite ETS-VII (credit: Space Robotics Laboratory, Tohoku University)

Figure 2: OSIRIS-REx, a well-known asteroid sampling mission, incorporating a robotic sampler element[403] (credit: NASA's Goddard Space Flight Center).

One of the most prominently proposed options to mitigate debris, deflect asteroids, sample asteroids, repair or refuel on-orbit systems, etc. is to use autonomous space manipulator systems. These systems are currently used for docking and handling payloads via teleoperation[165, 25]. There is a plethora of background knowledge about terres-

Figure 3: Canadarm2 on-board the ISS that assists with maintenance, docking, capturing payloads and EVAs (credit: NASA STS-114 Shuttle Mission Imagery)

trial and space manipulator systems (e.g., Canadarm2 on-board the ISS[108] seen in figure 3). Unlike other methods, space manipulators provide predictable control over the target behaviour, and more importantly, they are considered as the universal solution to performing various space missions. A space manipulator system consists of a spacecraft with a robotic manipulator arm mounted on it. The base spacecraft has all components of a satellite such as thrusters, Attitude Determination and Control System (ADCS), electronics, telemetry and other subsystems. Its payload, the robotic arm, will remain retracted until after the satellite is placed in orbit and it is deployed in later phases. There are 6 phases to an in-orbit space robotic mission: (i) close-range rendezvous and short range closing in maneuver, (ii) target identification, (iii) attitude synchronization with the target if needed, (iv) manipulator deployment, (v) capture and (vi) post-capture maneuvers.

On-Orbit Assembly of satellites, instruments or entire stations and maintaining them is another area of application of space manipulators. The most famous of them is Candarm2 (also referred to as Space Station Remote Manipulator System or in short SSRMS) on-board the ISS, which was developed by the Canadian Space Agency (CSA) and Macdonald Dettwiler and Associates (MDA) to aid in capturing incoming crew pods and payloads, assembling the ISS, and assisting astronauts in Extra-Vehicular Activities (EVA),[108] as demonstrated in Figure 3. Canadarm2 is the successor to Canadarm1 (also referred to as Shuttle Remote Manipulator System or in short SRMS) operated on the Space Shuttle to facilitate its docking, deployment and interaction with payloads and the ISS. A lesser-known (but by no means of low impact) is the Dextre (also referred to as Special Purpose Dexterous Manipulator or in short SPDM), a two-arm tele-operated robot that along with Canadarm2 is part of the Mobile Servicing System (MBS) on-board the ISS[71]. Dextre is another Canadian-built robot utilized on the ISS for repair operations that would otherwise require EVA by astronauts[2]. The natural progression of application of space manipulators will be their deployment in deep

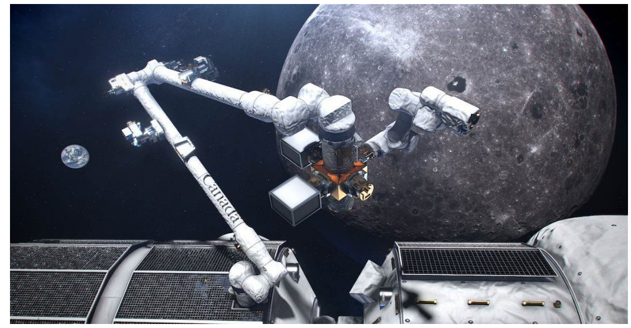

Figure 4: The new manipulator system set to assist reparations and maintenance of Lunar Gateway(credit: Canadian Space Agency)

space exploration missions, for assembly and maintenance of future space stations beyond low Earth orbits. The next generation of Canadian space manipulators will be sent to the Moon's orbit to assist in the exploration and establishment of a permanent Lunar Gateway, in collaboration with NASA. An artist's depiction of the early design of this manipulator, as envisioned by CSA, is visualized in Figure 4.

The current paper reviews the Guidance, Navigation and Control (GNC) methodologies used in various phases of in-orbit robotic missions conducted by a spacecraft-manipulator system. Robotic systems plan and perform tasks in three main steps: (i) estimating their current state and their environmental interactions (Navigation), (ii) generating a set of desired states according to the mission requirements and current state of the system (Guidance), and (iii) computing/exerting the control input to the system to follow the desired states (Control)[160]. The GNC methodologies are presented in a unifying fashion to provide a systematic comparison ground and list their capabilities and shortcomings. This enables both researchers and technology users to compare and choose between GNC methodologies for different phases of in-orbit robotic missions. Section 2 explains the main phases of the mission, their interplay, and the proposed GNC methodologies for each phase. In Section 3, kinematics and dynamics of a coupled spacecraft-manipulator system are breifly formulated based on screw theory and Euler-Lagrange equation for multi-body systems. The developed notation will be used throughout the paper to present the main ideas behind GNC methodologies. In section 4, synchronization techniques employed before arm deployment and their respective advantages and disadvantages are discussed. GNC methodologies for arm control in free-floating or free-flying operating regimes are thoroughly investigated in section 5. Optimal, Adaptive, Robust, variational and case-specific controllers are reported, formulated and explained in this section. Section 6 explains GNC methodologies for capture phase and post-capture maneuvers. Section 7 introduces two new families of approaches that can noticeably improve GNC of spacecraft-manipulator systems, i.e., reinforcement learning and geometric mechanics. Finally, disturbances in an orbital environment and their significance in GNC design are discussed in section

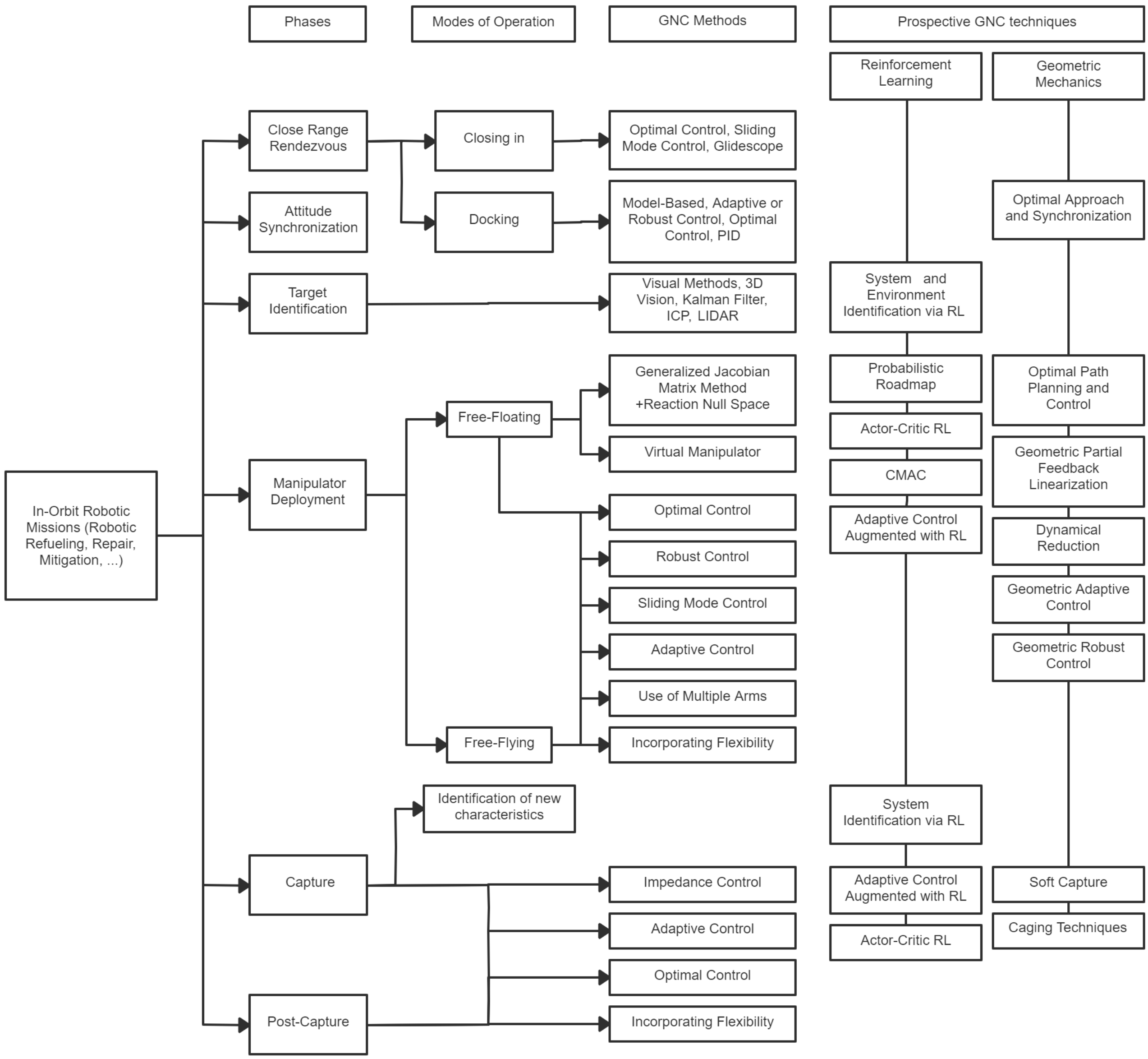

Figure 5: Flowchart description of the structure of the paper

8. The flow of information throughout this paper is visualized in Figure 5. This flowchart illustrates the aforementioned phases of an in-orbit robotic mission, breaks down the modes of operation in each phase and categorizes the commonly used and specialized GNC methods for different modes. On the right-hand sidehf of the chart the potential contributions of the two investigated families of GNC techniques are listed.

2. In-Orbit Robotic Mission Phases

A robot manipulator mounted on a spacecraft (hereon also referred to as space manipulator, spacecraft-manipulator or chaser-manipulator system) that moves in an orbital environment is a compelling universal solution to conduct space missions in the proximity of different space objects. The space manipulator is located in a parking orbit or at a station, before commencing the mission. It must perform orbital maneuvers to move to the target's orbit and rendezvous at a long range with it. In this scale, rendezvous means arriving at a-few-kilometer distance from the target[286].

2.1. Close-Range Rendezvous Maneuvers

Before the manipulator starts any operation, such as, capturing, docking, berthing, repairing, upgrading, assembling, etc., the chaser spacecraft must travel to the vicinity of the target, rendezvous and synchronize its orbital motion with the target[258]. Trajectories have been designed for a chaser to dock with a cooperative or non-cooperative target, assuming the availability of a docking device that consider both translational and rotational relative motion. The coupled attitude and position control problem for a chaser in a rendezvous with a non-cooperative target is investigated by Wei et al.[196] through the use of a robust sliding mode control. Park planned docking with a tumbling target using a nonlinear model predictive control[267] in two phases: (i) aligning the chaser with the entry cone of approach at the target, and (ii) performing a precise docking maneuver within the entry cone. Algorithms based on the Glidescope method are also proposed for autonomous docking to an orbital target as Nolet and Miller investigated by integrating and testing a variety of GNC algorithms on SHPERES microsatellites onboard ISS[250] to estimate the state of another target, plan the path and control the chaser motion[249]. Optimal path planning algorithms for rendezvous with an uncontrolled satellite form another family of control schemes that have been thoroughly investigated[216]. Boyarko's approach is an example that addresses minimum-time and minimum-energy rendezvous problem of a chaser with a tumbling target to achieve zero relative position and velocity[50].

2.1.1. Docking to the Target:

There is a rich background on underlying techniques of orbital rendezvous in different contexts such as planetary travel, orbital station-keeping and landing on smaller celestial bodies. The most notable of docking maneuvers were designed by the US and Russian space programs for orbital stations such as ISS and Mir. In their approach, Russians automated the docking process which is now considered essential for orbital robotic missions[386]. This problem has been addressed via different methods ranging from using a simple closed-loop PID controller or model-based (Clohessy-Wiltshire along with Euler equation) guidance and control law [157] to applying more advanced adaptive, optimal or Robust control schems. The dominant form of expressing the relative linear dynamics in this problem is through Clohessy-Wiltshire equations which is a simplified first order approximation of relative linear motion in circular orbits:

$$\begin{bmatrix}\delta r(\delta t)\\ \delta v(\delta t)\end{bmatrix} = \begin{bmatrix}\phi_{rr}(\delta t) & \phi_{rv}(\delta t)\\ \phi_{vr}(\delta t) & \phi_{vv}(\delta t)\end{bmatrix}\begin{bmatrix}\delta r_0\\ \delta v_0\end{bmatrix}, \tag{1}$$

where

$$\phi_{rr}(\delta t) = \begin{bmatrix}4-3\cos(n\delta t) & 0 & 0\\ 6(\sin(n\delta t)-n\delta t) & 1 & 0\\ 0 & 0 & \cos(n\delta t)\end{bmatrix}, \tag{2}$$

$$\phi_{rv}(\delta t) = \begin{bmatrix}\frac{1}{n}\sin(n\delta t) & \frac{2}{n}(1-\cos(n\delta t)) & 0\\ \frac{2}{n}(\cos(n\delta t)-1) & \frac{1}{n}(4\sin(n\delta t)-3n\delta t) & 0\\ 0 & 0 & \frac{1}{n}\sin(n\delta t)\end{bmatrix}, \tag{3}$$

$$\phi_{vr}(\delta t) = \begin{bmatrix}3n\sin(n\delta t) & 0 & 0\\ 6n(\cos(n\delta t)-1) & 0 & 0\\ 0 & 0 & -n\sin(n\delta t)\end{bmatrix}, \tag{4}$$

$$\phi_{vv}(\delta t) = \begin{bmatrix}\cos(n\delta t) & 2\sin(n\delta t) & 0\\ -2\sin(n\delta t) & 4\cos(n\delta t)-3 & 0\\ 0 & 0 & \cos(n\delta t)\end{bmatrix}. \tag{5}$$

The equations are expressed in the target's coordinate frame, δr is the relative linear position of the chaser with respect to the target, δv is the relative velocity of the two, n is the average orbital angular velocity, δt is the duration of the rendezvous maneuver, ϕ_{rr}, ϕ_{rv}, ϕ_{vr} and ϕ_{vv} are sensitivity matrices and the subscript 0 indicates initial conditions. The main form of expressing the relative attitude dynamics is through Euler's equation:

$$\begin{bmatrix}I_B & 0\\ 0 & I_T\end{bmatrix}\begin{bmatrix}\dot\omega_B\\ \dot\omega_T\end{bmatrix} + \begin{bmatrix}\omega_B\\ \omega_T\end{bmatrix} \times \begin{bmatrix}I_B & 0\\ 0 & I_T\end{bmatrix}\begin{bmatrix}\omega_B\\ \omega_T\end{bmatrix} = \begin{bmatrix}F_u + F_{eB}\\ F_{eT}\end{bmatrix} \tag{6}$$

Here, I_B and I_T are inertia matrices of the chaser and the target in their body coordinate frames, ω_B and ω_T are the body angular velocities of chaser and target in the same frame, F_u is the control torque and F_{eB} and F_{eT} are external disturbing torque in the body coordinate frames. Another approach to formulating relative dynamics of a chaser and a target in the chaser's coordinate frame is presented by Xing and Parvez[389]:

$$\begin{aligned}I_B \times \dot\omega_{BT} + \omega_{BT} \times I_B\omega_{BT} + \omega_{BT} \times I_B R^B_T\omega_T = \\ \tau_B - R^B_T(\tau_T + \Delta I_T \times \dot\omega_T + \\ \omega_T \times \Delta I_T\omega_T + 2\omega_T \times I_B\omega_{BT}),\end{aligned} \tag{7}$$

where

$$\tau_T = I_T \times \dot\omega_T + \omega_T \times I_T\omega_T, \tag{8}$$

and

$$\Delta I_T = R^T_B I_B R^B_T - I_T. \tag{9}$$

The relative angular velocity ω_{BT} is found from

$$\omega_{BT} = \omega_B - R^B_T\omega_T, \tag{10}$$

and the parameters are represented in their respective body coordinate frames. The matrix $R^B_T = (R^T_B)^{\mathbf{tr}}$ are the relative rotations between the target and the chaser coordinate frames (superscript $^{\mathbf{tr}}$ denotes the transpose of a matrix). Also, τ_B is the total external forces applied to the chaser spacecraft represented in the chaser coordinate frame.

Optimization methods can be coupled with these equations[218] using for example general Bolza type cost functions[217] of the form $J = \mu_t t_f + \mu_v|v|^2 + \mu_F|F_u|^2$ and realistic constraints on cost parameters[217] in the form of limitations on velocity $|R^B_T v| < v_{max}$ and command torque $|F_u| < F_{max}$. Here μ_t, μ_v, μ_F are weighting parameters in the cost function, t_f is the length of maneuver and v is the linear velocity of the chaser.

2.1.2. Closing in at a Safe Distance:

Various in-orbit robotic missions include chaser maneuvers to rendezvous with the target at a safe distance without docking. At this distance the chaser investigates the target in order to plan further closing in motions[41], for example, by estimating the relative orbital elements. After determining the approach direction, the chaser moves to the vicinity (a-few-meter distance) of the target from where the final stage of robotic capture or manipulation will be performed[375]. Some visual identifications may also be performed at this close-range rendezvous[287] . Rems, Risse and Benninghoff [288, 42] designed a GNC system for the German Aerospace Center (DLR) spacecraft that starts its close-range rendezvous at 15m. While approaching the target the system uses its visual capabilities (including a CCD camera, a Time-of-Flight camera and a LIDAR sensor) to estimate its target's pose, keep the target in sight and align itself with it. The identification continues to an 8m distance where the manipulation device is deployed. The chaser also flies around the target[100] at this range to identify the approach direction and then moves closer (3m) to have the target at the arm's reach.

2.2. Target Identification

A real-time estimation of the motion and inertia properties of the target is essential for planning a collision-free path for the arm and damage-free manipulation of the target. This task is often performed through image processing and model-based predictions when the target is non-cooperative. When servicing an operational satellite in orbit (e.g. robotic refueling, docking or repairing) this phase is less important as the object's motion and inertial parameters are relatively known. One of the simplest methods for target identification includes the use of fiducial markers[95] to identify the position of a number of points on the target which can provide a geometric means for estimating the relative orientation. The most dominant family of techniques to estimate the target's pose and motion uses Kalman Filter (KF)[16]. Recently, researchers have introduced 3D vision data manipulation techniques[8] for identification, for example, Iterative Closest Point (ICP) algorithm[22]. Other more complex approaches have also been investigated such as a cognitively controlled system by Qureshi et al.[281] that combines low level (detailed) feature tracking and high-level reasoning to make use of limited information for more reliable motion estimation.

Another feature of the target that must be identified in some in-orbit robotic operations is a grasping or docking point which will be targeted by the manipulator to latch on or dock to. Examples of such contact operations are debris removal, refueling, docking and assembly. If the target is cooperative, this point is known a priori; however, for a non-cooperative target with no docking port an appropriate grasping point has to be identified. The most significant criterion that should be considered is minimization of the contact forces and moments at the arm's side and the target's side upon impact, as is discussed in Nenchev and Yoshida's work [241]. They use reaction null-space to perform this minimization by sensing external forces at the end-effector and estimating their effects on different chaser components. Another identification criterion is to ensure that the grasping point always remains in the line of sight of the chaser-manipulator system. Second most noteworthy criterion is that the motion of the grasping point must be estimated and its position updated throughout the arm maneuver as the end-effector has to match both the position and velocity of the grasping point at the end of the arm deployment phase.

2.2.1. Visual Identification:

Visual tools are mainly used in remote target identification specifically in in-orbit robotic missions. Cameras are often mounted on the chaser spacecraft and on the end-effector to determine the state and properties of the target[149]. An example is utilizing ICP with 3D vision data by Aghili et al.[14]. In their work [14, 13, 291, 12], they integrated visual systems, a dynamic state estimator and optimal control methods to assist autonomous estimation in the close-range rendezvous phase. Using redundant tools, they propose a robust approach acquiring 3D images in harsh lighting conditions. For this purpose, they use a special camera developed in a separate work[291]. The method incorporates Triangulation, LIDAR sensor data and a model-based tracking to acquire visual data about pose and motion of the target. As an extension, they later added an adaptive Extended Kalman Filter (EKF) to predict the relative translational and rotational movement of the target with respect to the chaser spacecraft [18]. The performance of this state and inertia estimator in the presence of an occluded camera has also been validated[20] .

A visual servoing system has been proposed by Shademan[307] that is robust to uncertainties in the target model and calibration parameters (optical and configurational parameters of camera), and capable of dealing with unknown targets that performs well in harsh lighting conditions. The algorithm uses a robust M-estimator to determine the Jacobian matrix which describes the kinematics of motion. W. Xu [391] presents a comprehensive geometric approach to estimate the target's geometry and states using stereo vision measurements by the cameras mounted on both the arm and the chaser spacecraft while it rendezvouses with the target. Yazdkhasti also discusses vision-based relative navigation algorithm to identify an unknown and tumbling target and approach it[400]. Fourie et al. provide experimental evaluation of the performance of vision-based navigation systems for autonomous identification of a target in free-float[101]. G. Arantes in his thesis[31] discusses a visual method of real-time pose and motion estimation using KF for sequential state estimation, incorporating a monocular camera system. The above-mentioned model-based methods do not rely on markers on the target and are appropriate for identification of both cooperative and non-cooperative targets. Oumer presents a robust feature-based identification method in his thesis capable of providing an estimate of the target's motion even when lacking sufficient features by incorporating a point-wise motion model on all visible parts [256]. The method removes the complexities of some common methods dealing with the sunlight reflection on cameras or relying on heavy sensors such as LIDAR. Principal component analysis (widely used for handling data) is applied by Shi and Ulric to estimate the pose of an unknown satellite in proximity maneuvers[316]. As an example, e.Deorbit is a recent mission concept that incorporates visual servoing for tracking and minimizing position errors[147].

2.2.2. *Use of Kalman Filtering:*

Kalman filters and their extended forms are powerful estimation tools that have been extensively used in guidance, navigation and control of robotic systems operating in unknown environments. Several publications by F. Aghili[9] focus on use of laser-vision and KF to estimate the motion of a tumbling object and track the grasping point on it. Kalman filtering can also be coupled with other estimation methods to improve accuracy. Al-Isawi and Sasiadek [27] use an Adaptive Unscented Kalman Filter (AUKF) to estimate the dynamical states of the target, while extracting feature points via homography methods, finding the center of mass by employing ICP techniques and incorporating fuzzy logic adaptive control to reject disturbances. Adaptive KF can help estimate not only the states of the target but also its parameters[17] such as moments of inertia, centers of mass and rotation, and the principal axes. This filter can enhance the visual identification system by providing estimations even with occluded vision[20]. Photogrammetry is another identification method that is often utilized alongside enhanced KF[81]. The concept of utilizing several spacecraft for target identification has been explored by Zarei and Malaek[417]. They propose an unscented KF to combine information gathered from a coordinated network of satellites' range image data[415, 414, 416]. More recently, Cavenago developed Unscented and Extended KF using Differential Algebra (DA) techniques for pose estimation and contact detection purposes[57].

2.3. Attitude Synchronization:

The relative linear motion of the chaser and its target is synchronized in the close-range rendezvous phase. To prevent damage to docking mechanisms a docking spacecraft must remove any orientation and angular motion relative to the target[273]. Even in other robotic missions, for example, where a manipulator should go in contact with a target, performing attitude synchronization between the chaser and the target has multiple advantages[72]: (i) maintaining the line of sight and assisting the target identification, (ii) simplifying the arm motion planning by eliminating the need for the end-effector to chase the target, (iii) improving contact/docking performance by reducing the contact forces, and (iv) decreasing required Δv compared to having a fully actuated base[333, 384]. This synchronization becomes particularly crucial in tasks involving capturing, de-tumbling, docking to or repairing large targets with high rotational speeds such as de-orbiting EnviSat[273].

2.4. Manipulator Deployment:

The main phase of an in-orbit robotic mission involves deployment and autonomous motion control of the robotic arm from a braked position to reach the grasp point on the target. The chalenges in this phase include: (i) avoiding collision with any part of the target, chaser or other present objects[267], (ii) minimizing the contact forces between the end-effector[410] and the target upon reaching the grasping point, (iii) reliably following different features on the target, (iv) optimizing fuel/power consumption[85], (v) optimizing time of operation [296, 17], (vi) rejecting external disturbing effects[91, 146], (vii) considering the coupled dynamics of the arm and the chaser spacecraft[154], (viii) keeping the telemetry link with the control station[143], and (ix) maintaining line-of-sight to the target's grasping point.

There are two major approaches to the execution of manipulator deployment phase: (i) keeping the base spacecraft stationary, or (ii) letting the base float freely. The former has the benefits of maintaining better telemetry connection with a ground station and facing a relatively easier motion planning problem. The on-board AOCS system can keep the orientation of the base satellite still[137, 294] or a secondary arm can be utilized[154] to compensate the disturbances caused by the motion of the main arm. Free-floating scenario requires a lower Δv but complicates control of the arm as its motion influences the position and orientation of the base[369]. In this scenario often the reactions and disturbances transferred to the base satellite should be compensated[346, 86] or alternatively a secondary maneuver can be designed [346] to bring the base back to its initial attitude and to re-establish the telemetry link. When it is planned to keep the chaser's motion synchronized with the target a concurrent base-end-effector control must be proposed[64].

2.5. Capture:

The pivotal moment of an in-orbit robotic mission is when the end-effector goes into contact with the target at the grasping point. Compensating for the resulting contact forces is the main challenge in this phase[232]. Since these forces are function of the relative velocity of the contacting counterparts, a precise motion-planner in the previous phase that brings down this relative velocity to nearly zero [410] is advantageous. In the best-case scenario these contact forces still appear upon capture[192]; however, it is crucial to prevent them from harming the robotic system or the target. Researchers either consider the impact in the motion planning of the manipulator [63] to minimize the contact reactions, or they design for an end-effector impedance when the chaser-manipulator system is in the final configuration to withstand the contact[409].

2.6. Post-Capture Maneuvers:

In the post-capture phase, the target and the chaser are brought into a relative configuration to facilitate accomplishing the main objective of the in-orbit robotic operation, whether it be repairing (e.g. replacing parts) [329], refueling [349], structure assembly[426], re-orbiting [411] or debris mitigation[310]. The tasks in this phase include (i) detumbling or re-orienting the target relative to the chaser[381] (e.g. by transferring its angular momentum to the chaser's compensation devices[79]), (ii) orienting and re-configuring the chaser-manipulator system to prepare for the final mission objective and to establish telemetry connection, and (iii) aligning or rigidizing the arm[311]. The choice of the post-capture maneuvers is highly dependant on the planning of the capture phase[76, 75]. After the capture the chaser spacecraft and the target will either act like a unified dynamical object[229] or have significantly coupled dynamics even if they do not rigidly join[6]. The fact that the target has partially known dynamical properties[7] of flexible components[104] requires designing post capture maneuvers for parameter identification for the joined system[3, 282]. Stability and safety of the chaser-manipulator-target system must be guaranteed while performing the system identification[246].

3. Kinematics and Dynamics of Spacecraft-Manipulator Systems

A spacecraft-manipulator system is best represented as a multi-body system consisting of rigid bodies interconnected by ideal joints. It is critical to obtain a simple and yet geometrically meaningful model of the system that is capable of including the distinguishing characteristics of space manipulators. One such characteristic is possessing a freely moving 6-Degree-of-Freedom (DoF) base body (spacecraft) resulting in a coupled dynamics between the spacecraft and the arm[90]. The base spacecraft is attached to one or more arms, each having multiple links modelled as a chain of rigid bodies. The last link is normally the end-effector that is used to manipulate the target. Many formalisms have been proposed to model multi-body systems, among which screw theory for kinematics[231] and Hamiltonian/Lagrangian formulation for dynamics[330, 65] are particularly advantageous due to their strong geometric roots. In this paper, the language of screws and a Lagrangian formulation are used to briefly describe the kinematics and dynamics of spacecraft-manipulator systems, which forms a basis to unify the formulation of various GNC approaches. In later sections, more advanced models will be described that are founded upon this formulation with added nuances or entirely new approaches suitable for capturing certain properties of the system.

In the literature, space manipulator systems are usually modelled as a branch of rigid bodies interconnected through single DoF joints. This model is assumed throughout the kinematics and dynamics analysis of space manipulators. The inertial coordinate frame and the end-effector are labelled by I and ee, respectively. Body 1, labelled by b, is the spacecraft that is free to move in all directions, whose state vector is denoted by $\theta_b \in \mathbb{R}^6$. The manipulator is assumed to have n DoF with the state vector $\theta_m \in \mathbb{R}^n$. Hence, the state of the space manipulator system is well-defined through the vector $\theta = [\theta_b^{\mathbf{tr}}, \theta_m^{\mathbf{tr}}]^{\mathbf{tr}} \in \mathbb{R}^{6+n}$. A relative pose of Body i

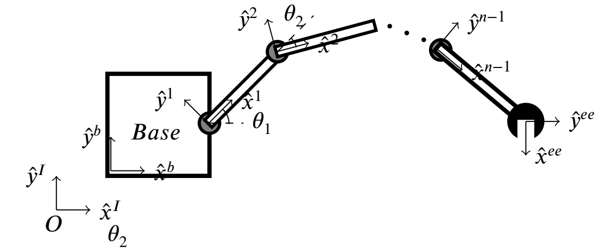

Figure 6: Spacecraft-manipulator system

with respect to Body j can be represented by the homogeneous transformation

$$H_i^j = \begin{bmatrix} R_i^j & {}^j p_i^j \\ 0 & 1 \end{bmatrix}, \tag{11}$$

where R_i^j is the relative orientation between Body i and Body j, ${}^j p_i^j$ is the relative translation from Body j to Body i and the preceding superscript ^{j} always means that the vector is expressed in the coordinate frame of body j. The forward kinematics map, describing the position and orientation of the end-effector with respect to the inertial coordinate frame, becomes:

$$H_{ee}^I(\theta) = H_b^I(\theta_b) H_1^b(\theta_1) H_2^1(\theta_2) ... H_{ee}^{n-1}(\theta_n). \tag{12}$$

Each transformation depends on the joint parameters describing the relative pose between two interconnected bodies, which is a vector θ_b for the base and θ_i ($i = 1, \cdots, n$) for the i^{th} joint of the manipulator; thus, $\theta_m = [\theta_1, \cdots, \theta_n]^{\mathbf{tr}}$.

A relative twist ${}^I V_i^j$ describes the infinitesimal relative motion of the i^{th} body with respect to the j^{th} body and expressed in the inertial coordinate frame. The Jacobian ${}^I J_{ee}^I \in \mathbb{R}^{6\times(6+n)}$ is a mapping from the base velocity and the speed of manipulator joints to the relative twist ${}^I V_{ee}^I$ corresponding to the velocity of the end-effector in the inertial coordinate frame, which takes the following form[231]:

$$\begin{aligned} {}^I J_{ee}^I(\theta) &= \begin{bmatrix} {}^I T_b^I & {}^I T_1^b & {}^I T_2^1 & \dots & {}^I T_n^{n-1} \end{bmatrix} \\ &=: \begin{bmatrix} J_b(\theta_b) & J_m(\theta) \end{bmatrix}, \end{aligned} \tag{13}$$

where $J_b = {}^I T_b^I = \mathbf{Ad}_{H_b^I(\theta_b)} \in \mathbb{R}^{6\times 6}$, if the base velocity is considered as the instantaneous body twist of the base, and $J_m \in \mathbb{R}^{6\times n}$ is formed by the columns ($i = 1, \cdots, n$),

$${}^I T_i^{(i-1)} = \mathbf{Ad}_{H_i^I} \left((H_i^{i-1})^{-1} \frac{\partial H_i^{i-1}}{\partial \theta_i} \right)_{\times} \in \mathbb{R}^{6\times 1}. \tag{14}$$

Here for an arbitrary homogeneous transformation H_i^j, the Adjoint operator $\mathbf{Ad}_{H_i^j}$ is defined as

$$\mathbf{Ad}_{H_i^j} := \begin{bmatrix} R_i^j & 0 \\ ({}^j p_i^j)^{\times} R_i^j & R_i^j \end{bmatrix}, \tag{15}$$

where super- and sub-script $\times$ denote the mapping from a vector to the corresponding skew-symmetric matrix and its inverse, respectively. Note that when the super- or sub-script is equal to 0 or n it refers to the base body (b) or the end-effector (ee). The relative twist of each body with respect to the inertial coordinate frame and expressed in the inertial frame is then calculated from

$$ {}^{I}V_{ee}^{I} = {}^{I}J_{ee}^{I}(\theta)\dot{\theta} = J_b(\theta_b)\dot{\theta}_b + J_m(\theta)\dot{\theta}_m. \quad (16)$$

Using body velocities and the explained means of formulating the kinematics of the spacecraft-manipulator, the dynamics of the system can be formulated via the Lagrangian approach as

$$\begin{bmatrix} M_b & M_{bm} \\ M_{mb} & M_m \end{bmatrix} \begin{bmatrix} \ddot{\theta}_b \\ \ddot{\theta}_m \end{bmatrix} + \begin{bmatrix} C_b & C_{bm} \\ C_{mb} & C_m \end{bmatrix} \begin{bmatrix} \dot{\theta}_b \\ \dot{\theta}_m \end{bmatrix} + \begin{bmatrix} N_b \\ N_m \end{bmatrix} = \begin{bmatrix} B_b & 0 \\ 0 & B_m \end{bmatrix} \begin{bmatrix} \tau_b \\ \tau_m \end{bmatrix}. \quad (17)$$

Here, M_b is the 6×6 mass matrix corresponding to the overall spacecraft-manipulator system at a system configuration θ, M_m is the $n \times n$ generalized mass matrix corresponding to the manipulator, and $M_{bm} = M_{mb}^{\mathbf{tr}}$ is the $6 \times n$ matrix representing the coupled inertia between the base and the manipulator. The mass matrices are determined by

$$M_b = \sum_{l=b,1}^{n} \left({}^{I}T_b^{I}\right)^{\mathbf{tr}} \mathbf{Ad}_{H_l^I}^{-\mathbf{tr}} \mathcal{M}_l \, \mathbf{Ad}_{H_l^I}^{-1} \left({}^{I}T_b^{I}\right), \quad (18)$$

$$[M_{bm}]_j = \sum_{l=b,1}^{n} \left({}^{I}T_b^{I}\right)^{\mathbf{tr}} \mathbf{Ad}_{H_l^I}^{-\mathbf{tr}} \mathcal{M}_l \, \mathbf{Ad}_{H_l^I}^{-1} \left({}^{I}T_j^{I}\right), \quad (19)$$

$$[M_m]_{ij} = \sum_{l=1}^{n} \left({}^{I}T_i^{I}\right)^{\mathbf{tr}} \mathbf{Ad}_{H_l^I}^{-\mathbf{tr}} \mathcal{M}_l \, \mathbf{Ad}_{H_l^I}^{-1} \left({}^{I}T_j^{I}\right), \quad (20)$$

where $\mathcal{M}_l$ is the constant mass matrix of body l in its own coordinate frame. Equation 19 calculates the j^{th} column of M_{bm} and Equation 20 presents the ij-element of the matrix M_m, where $i, j \in \{1, ..., n\}$. Here, ${}^{I}T_b^{I}$ and ${}^{I}T_j^{I}$ are respectively the block matrices of the Jacobian corresponding to the base spacecraft and the j^{th} manipulator link with respect to and expressed in the inertial coordinate frame.

Similarly, the block components $C_b \in \mathbb{R}^{6\times 6}$ and $C_m \in \mathbb{R}^{n\times n}$ are the matrices of Coriolis and centrifugal forces corresponding to the whole system and the manipulator, respectively. The coupled Coriolis and centrifugal effects are captured by $C_{bm}, C_{mb}^{\mathbf{tr}} \in \mathbb{R}^{n\times 6}$. Let M be the collection of all mass matrices and C be the collection of Coriolis and centrifugal matrix blocks. Elements of the C matrix are defined as

$$C_{ij} = \sum_{k=1}^{6+n} \frac{1}{2}\Big(\frac{\partial M_{ij}}{\partial \theta^k} + \frac{\partial M_{ik}}{\partial \theta^j} - \frac{\partial M_{kj}}{\partial \theta^i}\Big)\dot{\theta}^k, \quad (21)$$

where θ^k is the k^{th} element of the vector $\theta \in \mathbb{R}^{6+n}$. The vectors $N_b \in \mathbb{R}^6$ and $N_m \in \mathbb{R}^n$ are the potential forces corresponding to the base and the manipulator DoF, respectively:

$$N_b = \frac{\partial}{\partial \theta_b} U(\theta) \quad \& \quad N_m = \frac{\partial}{\partial \theta_m} U(\theta), \quad (22)$$

where $U(\theta)$ is an external potential field acting upon the system. The matrices $B_b \in \mathbb{R}^{6\times 6}$ and $B_m \in \mathbb{R}^{n\times n}$ are the collections of control directions in the base and the manipulator, respectively. Finally, the vectors $\tau_b \in \mathbb{R}^6$ and $\tau_m \in \mathbb{R}^n$ respectively denote the control inputs at the base and the manipulator.

4. GNC for Attitude Synchronization

As discussed in section 2.3, angular motion synchronization is advantageous for several reasons: enhanced target identification[273], improved arm trajectory planning[72] and control, performing damage-free contact and fuel conservation[333, 384]. An extensive discussion on linear/angular motion synchronization in an in-orbit robotic operation has been presented by Colmenarejo and collaborators[72]. They propose 3 scenarios: (i) keeping the chaser stationary in front of the selected grasping point throughout the arm operation, (ii) keeping the end-effector stationary with respect to the grasping point by passively rotating the chaser about target's axis of rotation, and (iii) only keeping the chaser stationary in the orbital (non-rotating) frame and actively controlling the manipulator motion to follow the grasping point. In the first scenario, the chaser must approach the target over its spin axis, then fly around it to follow the grasping point which will result in the least complex arm motion, but require the highest Δv. This approach is most suitable for fast spinning targets. The second scenario results in a slightly more complex arm motion but less fuel expenditure. This approach works the best for slowly spinning targets with a fixed spin axis. The third scenario needs the most complex arm control and due to the need for possible cyclic motion it may require more power than the previous scenarios, specially when the target is spinning fast. This approach works the best for stationary targets. GNC methodologies for the first scenario have been developed in [384, 424] . Welsh and Subbarao developed an adaptive control algorithm that breaks down the synchronization procedure into two linear and rotational phases: (i) maintaining a safe relative linear position between the chaser and the target along the direction of the target's docking point, and (ii) re-orienting the attitude of the chaser spacecraft to align the on-board robotic device with the constant relative position vector[384]. They later designed a nonlinear controller resistant to the environmental disturbances to accomplish the aforementioned synchronization task[333]. In this work, they utilize a virtual reference target to command the desired chaser attitude. Similarly, Yan-wei and Le-Ping developed a two-phase 6-DoF synchronization procedure using an adaptive control method robust against internal uncertainties, with the specific purpose of decreasing the time of operation of the arm[424].

Although not explicitly focused on chaser-manipulator systems, there is a rich body of work on attitude synchronization for on-orbit docking and satellite formation flying[191, 54], which can be extended to other in-orbit robotic missions. Wang, Hadaegh and Lu[55] demonstrate that even a simple PID controller is capable of coordinating the relative attitude and linear motion of multiple free-floating satellites. The attitude synchronization of a robotic spacecraft must be resilient to uncertainties arising from system identification and environmental disturbances. Li and Kumar[183] propose a centralized sliding-mode control for the tracking task in a formation flying scenario, where the satellites follow a lead spacecraft and a fuzzy adaptive controller accounts for the system uncertainties. Wu, Wang and Poh[387] also incorporate sliding-mode control structures to decentralize the control problem and separately synchronize the attitude of several spacecraft in formation flying, in presence of uncertainties. A compound control law consisting of a nonlinear feedback control logic and a compensator was demonstrated robust by An, Lu and Ren[30] to perform attitude synchronization for docking purposes. Chung, Ahsun and Slotine[70] propose a decentralized tracking control law based on oscillator phase and a Lagrangian, enabling a concurrent nonlinear control of both attitude and linear motion of a fleet of spacecraft. This capability is particularly beneficial in capture missions dealing with complicated tumbling motion of a target that requires both a fly-around and an axial synchronization.

Attitude synchronization has also been investigated for docking in on-orbit servicing missions. For example, Subbarao and McDonald take advantage of multi-sensor fusion navigation techniques to plan the rendezvous and docking[332]. Subbarao and Welsh propose adaptive synchronization to maintain relative position and proper orientation while docking or capturing a free-floating spacecraft[333]. Yun-hai et al. develop an adaptive tracking control to synchronize the attitude of the chaser with that of the target during OOS of a non-cooperative target[106]. Xueyan, Zhang and Wei also designed an attitude synchronization control law based on a terminal sliding mode control method for docking to a tumbling target[394]. Lu, Geng and Shan's work proposes an autonomous docking procedure to a tumbling orbital object via a robust optimal sliding mode control scheme[197].

5. GNC for Arm Control

As discussed in section 2.4, GNC of arm movement is one of the core focuses of research in an in-orbit robotic mission. Motion of the arm cannot be studied independently of that of the spacecraft. Trajectory planners have been extensively studied for such coupled systems[138, 59, 166]. Since the robustness and stability of the trajectory following tasks are crucial in in-orbit missions, closed-loop control systems have also been thoroughly investigated[301, 270, 302]. The initial configuration and velocity of the chaser-arm system in this phase is dictated by the terminal states of the chaser at the end of the rendezvous or synchronization phase[197, 106]. Further, the terminal relative conditions, i.e., positioning of the end-effector at the capture point, are specified by the identification phase[17, 20, 307, 15]. Meanwhile, the coupling dynamics between the base spacecraft and the arm[78] along with the environmental effects[301] are the main factors considered in the GNC of the arm.

The mission planner either actively keeps the base satellite stationary throughout arm motion (free-flying scenario)[178], or assigns a pre-designed passive or active trajectory for the base [227], or allows the base to move freely (free-floating scenario)[137]. In the literature, the free-flying and free-floating scenarios are investigated the most. Fixing the base requires solving the problem of station-keeping[72], while on the other hand a free-floating spacecraft-arm introduces the challenge of non-holonomic arm trajectory planning[6] and control. The consensus among the scientific society is that the ADCS system should be turned off when the end-effector goes into contact with the target to avoid any unexpected response of the control system. Therefore, it is always necessary to plan a free-floating scenario for the robotic system. The primary concern that has been addressed in the literature in the free-floating scenario is to minimize the disturbances on the base spacecraft caused by the arm motion. In the free-flying systems, however, the main concern is to minimize the power consumption while robustly keeping the telemetry link[85]. Other challenges may also arise due to non-holonomicity of the arm dynamics such as dynamic singularities[261, 343] and the need for smooth obstacle avoidance[265, 293]. A dynamic singularity occurs when the generalized Jacobian matrix[365] (See section 5.1.2) becomes singular. Tchon, Respondek and Ratajczak addressed this problem by utilizing normal forms of singularities of non-holonomic robots described by control-affine systems[343]. In the mission concept level, designing a spacecraft-arm system compatible with various missions is desirable. Reconfiguration, modularity[19, 21], variational-structure control[196, 39], robustness and adaptability[360, 362, 298], or use of multiple manipulators [264] can address this need. Aghili et al. propose a reconfigurable arm having several passive joints that can be locked in certain configurations[21, 19]. Challenges may stem from the uncertainties in the chaser-arm system and its environment, for example, uncertainties in the target model[3], unaccounted elastic behaviours in the robotic system or the target[277, 144], and external and internal disturbances[114, 61] . Therefore, advanced control methodologies capable of handling uncertainties, such as adaptive, robust and sliding mode controllers[297, 356, 353] have been extensively studied in the literature for spacecraft-manipulator systems. Table 1 collects the core ideas behind the GNC methodologies presented throughout this section and compares their performance.

5.1. Base Spacecraft in Free Float

Controlling a free-floating space robot is more complicated than a free-flying robot due the un-actuated 6 DoF of its base[348]. This, as a mathematical problem, is similar to losing the actuation capabilities at some of the joints in a

Table 1
Summary of GNC methodologies in the manipulator deployment phase

GNC Method	Core Formulae	Advantages	Disadvantages
Generalized Jacobian	$J_g = J_m - J_b M_b^{-1} M_{bm}$	- Relating end-effector and joint velocities for free floaters with zero momentum - Facilitating task-space control - Facilitating minimization of coupling disturbances on the base spacecraft	- Considering only zero momentum - Resulting controllers not being Resilient against external disturbances
Virtual Manipulator	$X_{ee} = X_{VG} + V_1(\theta) + V_2(\theta) + ... + V_n(\theta)$	- Reducing the dynamics of free-floating manipulators at zero momentum - Facilitating the application of control methods for fixed-base manipulators - Facilitating the control of coupling disturbances on the base spacecraft	- Considering only zero momentum - Not being suitable for free-fliers and externally disturbed space robots
Optimal Control	$\tau_m^* = \underset{\tau}{\mathbf{argmin}}\{\Pi(\theta(t_f), \dot{\theta}(t_f)) + \int_{t_0}^{t_f} \mathcal{L} dt\}$	- Being the base for other GNC techniques - Minimize fuel consumption/ time of operation/ jerk/ base disturbance - Including constraints and actuator limits	- Being numerically cumbersome - Being limited when applied to non-convex problems
Adaptive Control	$\tau_m = K_e(t)e + K_{x_m}(t)x_m + K_{v_m}(t)v_m$	- Adapting to unknown space environment - Handling unknown targets in capture and post-capture phases - Offering unified controllers for pre-capture, capture and post-capture phases	- Being prone to instability, when facing unaccounted disturbing sources - Poor handling of actuator saturation and constraints - Being computationally involved
Robust Control	$\begin{bmatrix} \tau_b \\ \tau_m \end{bmatrix} = -R^{-1} B^{\mathbf{tr}} T_0 \begin{bmatrix} e_b \\ e_m \end{bmatrix}$	- Being resilient to orbital disturbances - Optimizing fuel consumption - Being safe and practical	- Depending on model accuracy - Being hard to find a solution when dealing with non-convex optimizations - Being too slow and conservative
Sliding Mode Control	$\tau_m = -\hat{M}_s^{-1}(\hat{f}_s + \dot{s}_r + k\mathbf{sgn}(s))$	- Eliminating identifiable disturbances[221] - Working with uncertain models - Adapting to changing parameters[388] - Rejecting external disturbances	- Chattering in control input - Losing too much fuel - Damaging actuators due to high-frequency commands
Use of Multiple Arms	${}^I V_{ee}^{I(k)} = {}^b J_{ee}^{(k)} \dot{\theta}_b + {}^m J_{ee}^{(k)} \dot{\theta}_m = J_g^{(k)} \dot{\theta}_m$	- Performing multiple tasks - Enjoying redundancy and reconfiguration - Concurrently controlling base/arms	- Being too heavy to launch - Being too complex to be safely controlled - Consuming too much fuel
Incorporating Flexibility	$J_I \ddot{\theta}_I + K(\theta_I - \theta_m) = \tau_m$ $M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} - \begin{bmatrix} 0 \\ K(\theta_I - \theta_m) \end{bmatrix} = 0$	- Including realistic structural dynamics - Saving fuel by suppressing vibrations - Decreasing modelling uncertainties - Accounting for flexibility in controllers	- Complicating the dynamics and control - Slowing down the response - Computationally involving

multi-body system[266]. On one hand, the un-actuation introduces challenges for the trajectory planning and control of the system, and on the other hand, it enables development of energy efficient control strategies[262] by making use of the internal couplings and the degree of controllability of the system[139]. The initial relative position between the spacecraft and the target's centers of mass is another commonly overlooked factor that becomes critical in path-planning due to the stationary nature of center of mass of the whole spacecraft-arm system in the orbital frame (unless disturbances are considered)[419]. Based on the formulated dynamics in Section 3, the general dynamical equation describing the motion of a free-floating spacecraft-arm system does not include any applied control command to the base. Frequently in the literature, the local effects of any potential such as gravity and Earth's magnetic field are neglected and disturbances are not considered. Therefore, Equation 17 can be rewritten in the following form:

$$\begin{bmatrix} M_b & M_{bm} \\ M_{mb} & M_m \end{bmatrix} \begin{bmatrix} \ddot{\theta}_b \\ \ddot{\theta}_m \end{bmatrix} + \begin{bmatrix} C_b & C_{bm} \\ C_{mb} & C_m \end{bmatrix} \begin{bmatrix} \dot{\theta}_b \\ \dot{\theta}_m \end{bmatrix} = \begin{bmatrix} 0 \\ \tau_m \end{bmatrix}. \quad (23)$$

Since it is assumed that no external force/torque is applied to the system, the total momentum of the system in the inertial coordinate frame is conserved:

$$P_{tot} = J_b^{-\mathbf{tr}} \frac{\partial L}{\partial \dot{\theta}_b} = J_b^{-\mathbf{tr}} \left[M_b \dot{\theta}_b + M_{bm} \dot{\theta}_m \right] = const. \quad (24)$$

A common practice is to keep the momentum zero.

$$P = M_b \dot{\theta}_b + M_{bm} \dot{\theta}_m = 0. \quad (25)$$

In a zero-momentum system, the attitude of the base is dependant on the path that the manipulator joints take. Two different paths bringing the arm from one starting configuration to one ending configuration might result in different base satellite attitudes[402]. Nevertheless, some researchers such as Seweryn and Sasiadek developed trajectory optimization methods that take into consideration nonzero angular momentum of the base spacecraft or external forces acting on it [295, 133]. The property of interest in the control and trajectory planning of an arm is mainly the absolute angular and linear velocity of the end-effector that is found from Equation 16.

The challenges in path-planning of free-floating space manipulators have been approached in various research works. Ulrich and collaborators compare the trajectory-tracking capabilities of simple feedback controllers such as PID logic to more advanced control approaches such as adaptive control schemes[360]. A common addressed challenge in the control of a free-floating robot is how to deal with the reactions acting on the base spacecraft[90]. Adaptive and robust controllers provide a strong means to tackle the problem of unwanted base motion[28]. Dimitrov investigates several problems arising from the coupling between the dynamics of the base and the manipulator specially to plan reactionless arm maneuvers. He introduces holonomic distribution control, using bias angular momentum and distributed momentum control for post-capture planning [78]. Al-Isawi uses an adaptive unscented KF and a homography matrix to estimate the unknown inertia and pose of the target, and he suggests an adaptive fuzzy logic system to control a free-floating spacecraft-arm system[27]. In the following sections, several families of solutions to the trajectory planning and control of free-floating systems will be studied.

5.1.1. Optimal Control

In an optimal control strategy the command signal is chosen such that to optimize a property of choice while bringing the system described via Equation 23 from a starting condition $\theta(t_0) = \theta_0$ to a final condition $\theta(t_f) = \theta_f$[374]. The considered cost function is normally a functional depending on the state trajectory and the control input to the system[345, 98]:

$$A = \Pi(\theta(t_f), \dot{\theta}(t_f)) + \int_{t_0}^{t_f} \mathcal{L}(\theta(t), \dot{\theta}(t), \tau_m(t))dt, \quad (26)$$

which is optimized subject to the dynamics

$$\ddot{\theta}(\theta, \dot{\theta}, \tau_m) = -M(\theta)^{-1}C(\theta, \dot{\theta})\dot{\theta} + M(\theta)^{-1}B(\theta)\begin{bmatrix} 0 \\ \tau_m \end{bmatrix}. \quad (27)$$

The cost or performance index consists of two parts: (i) an endpoint cost Π dependant on boundary conditions of the trajectory, and (ii) an integral cost term involving a Lagrangian $\mathcal{L}$ depending on the evolution of the states and the control command[233]. Time of operation, fuel cost, base disturbance and length of the path are examples of common cost functions included in control of space robots. In a series of works by Aghili et al. optimal control formulations are presented for both pre-grasp and post-grasp maneuvers[10, 7]. The cost function they propose aims to minimize the time of operation $(t_f - t_0)$, arm end-effector linear motion in the base spacecraft coordinate frame $({}^b\dot{p}^b_{ee})$, control command (τ_m) and fuel cost[5, 6]:

$$A = \int_{t_0}^{t_f} (1 + k_1|{}^b\dot{p}^b_{ee}|^2 + k_2|\tau_m|^2)dt, \quad (28)$$

where ${}^b p^b_{ee}$ is the position of the end-effector with respect to and expressed in the base spacecraft coordinate frame. This formulation yields the optimal control signal[5]

$$\tau^*_m = {}^b\ddot{p}^b_{ee} = \frac{\lambda_{m2}}{2k_2}, \quad (29)$$

with λ_{m2} being a costate evolving based on

$$\ddot{\lambda}_{m2} = -\frac{k_1}{k_2}\lambda_{m2}. \quad (30)$$

The optimal trajectory is obtained from the differential equation

$$\frac{d^2}{dt^2}({}^b\ddot{p}^b_{ee} - \frac{k_1}{k_2}{}^b p^b_{ee}) = 0. \quad (31)$$

Particle swarm optimization (PSO) is another commonly utilized optimization technique in in-orbit robotic missions[154, 418]. A particle swarm is a set of optimization vectors[380, 381] such that each vector includes the performance parameters, e.g., fuel cost and motion of joints[380, 390], which go through a series of small-scale optimization steps. A choice of cost function is the exerted disturbances on the spacecraft by arm motion that cost extra fuel and cause loss of telemetry link. In a research by Zhang et al. trajectory optimization is performed via PSO to minimize the disturbances on the base spacecraft[418]. In another approach by Xu, a Genetic Algorithm (GA) is incorporated to find optimal paths to control the arm and base simultaneously[391, 393]. Another instance of use of GA can be seen in Huang, Chen and Xu's work[131] that generates an optimal trajectory that exerts the least amount of disturbance on the base. When incorporating flexible linkages to make use of their nonlinear behaviour or to better model the arm (see Section 5.6), undesired elastic vibrations are introduced to the system that generally should be minimized[277]. Jankovich and Kirchner use the coupling between the base and the arm in their nonlinear trajectory optimization technique via an orthogonal collocation method to minimize the overall angular momentum of the system[148].

Another optimal control technique, based on Piazzi and Visioli's work[275], aims to find arm paths that minimize the second derivative of joint velocities and base orientation (jerk). The strength of this method, distinguishing it from other optimal control techniques, lies in the similarity of its generated trajectories to human motion and its resilience to vibrations. The cost function in this method is defined as the total jerk in the system that need be minimized. Trajectories that are considered in this method are piece-wise continuous curves, which are usually characterized via polynomials for each degree of freedom.

In an early attempt, DeSilva also proposed a trajectory planner based on acceleration and jerk limits[77], which exploited the redundancy of space manipulators. Various optimization techniques can be applied to improve the performance of this strategy. Jerk can also be a partial performance index in a multi-objective optimization[193]. Jerk minimization has been incorporated to improve the efficiency of a genetic-based optimal control by Huang[136, 132]. A GA optimization (similar to PSO) follows a procedure depicted in Figure 7.

5.1.2. Generalized Jacobian Matrix and Reaction Null Space

Some of the pioneering control methods for moving-base manipulators incorporated the concept of Generalized Jacobian Matrix (GJM)[363] that was first introduced by Yoshida and Umetani[365]. They further analyzed and tested this tool, encouraging many other researchers to employ it for kinematics, dynamics and control analysis[413]. As the free-floating system is commonly assumed to be initially at rest, in this approach the momentum is kept constant at zero,

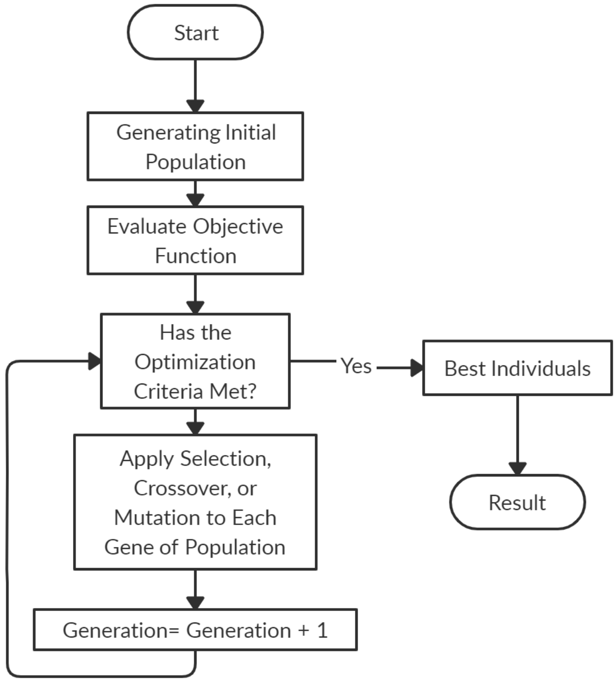

Figure 7: GA (and similarly PSO) optimization procedure[136]

i.e., $const. = 0$ in Equation 25. Therfore,

$$\dot{\theta}_b = -M_b^{-1} M_{bm} \dot{\theta}_m. \tag{32}$$

Substituting into Equation 16,

$$^I V_{ee}^I = J_m \dot{\theta}_m - J_b M_b^{-1} M_{bm} \dot{\theta}_m, \tag{33}$$

and the GJM

$$J_g := J_m - J_b M_b^{-1} M_{bm}. \tag{34}$$

This Jacobian directly relates the joints' motion to the end-effector motion when the system has zero momentum. Nenchev and Yoshida later improved this method via introducing the bias angular momentum approach that is based on minimizing the base motion when planning an arm trajectory[404]. They also used the same viewpoint to minimize the base motion in post-capture[241, 242]. The GJM concept can also be utilized to analyze workspace of a moving-base manipulator. Yoshida and Umetani used a Guaranteed WorkSpace (GWS) extracted from GJM formulation to test and demonstrate the applicability of their approach[412, 364].

Reaction Null-Space (RNS) was introduced as a tool to determine the joint velocities that minimize the reaction exerted on the base[403]. The states of the manipulator were partitioned to take advantage of the redundancy in the system and the integrability of the 1D distribution resulted from RNS to introduce trajectories with zero reaction on the base[405].The joint accelerations that cause zero reaction take the following form:

$$\ddot{\theta}_m = -M_{bm}^{+} \dot{M}_{bm} \dot{\theta}_m + (I - M_{bm}^{+} M_{bm})\xi, \tag{35}$$

where A^+ is the right pseudoinverse of the matrix A, $(I - M_{bm}^{+} M_{bm})$ is the projection onto the null space of M_{bm}, and ξ is an arbitrary vector. Kaigom used time-varying polynomials to span a basis of the RNS and formulate the joint velocities in this space. He then employed constrained particle-swarm optimization to find the optimal joint trajectories[154]. Nenchev et al. developed a composite controller for workspace path tracking of a manipulator mounted on a flexible base, such as to avoid disturbances on the flexible base through utilizing RNS[239]. Many control techniques are built upon above-mentioned approaches to take advantage of their simplified formulation. For example, an optimization based on genetic algorithms was used to address the non-holonomicity of the system [393], an optimal solution is introduced that takes advantage of the redundancy in the system[239, 24, 405], a digital control scheme is proposed for the space manipulator system[337], and control techniques were suggested to extend the robotic concept solution to manipulators mounted on flexible base structures [243] or multiple manipulators working in parallel or in coordination[407].

5.1.3. Virtual Manipulator Approach

Vafa and Dubowsky first presented the idea of a Virtual Manipulator (VM)[369] as an analytical means to study the degrading dynamical effects of the coupling between the base spacecraft and the manipulator. A VM is an imaginary fixed-base manipulator that is dynamically equivalent to an arm mounted on a spacecraft. Since it is fixed-base, traditional approaches can be used to analyze the dynamic behaviour of the arm on a free-floating object or design controllers for such a system[87]. Kinematics of the arm, the base and the payload can be represented in terms of the motion of the virtual manipulator[370]. The VM has its base at the Center of Mass (CoM) of the spacecraft-manipulator system. If no external forces act on the system it is possible to place the inertial frame at the system's CoM, and hence, the base of VM remains stationary. This stationary point is known as the Virtual Ground (VG)[369].

$$X_{VG} = \frac{X_b m_b + \sum_{i=1}^{n} X_i m_i}{m_b + \sum_{i=1}^{n} m_i}, \tag{36}$$

where X_i shows the vectorial position of the CoM of the i^{th} link and X_b is that of the base, m_i represents the mass of the i^{th} link and m_b is that of the base, and X_{VG} is the position vector of the VG. The first joint of the VM is a ball joint that represents the orientation of the base satellite and the rest of the joints correspond to those of the real arm. Each revolute joint of the VM has an axis of rotation parallel to its equivalent joint in the real manipulator and rotates the same angle[371]. Each link of the VM, though, is defined by the vector V_i

$$V_1 = D_1 \quad \& \quad V_i = H_i + D_i \; (i = 2, \cdots, n), \tag{37}$$

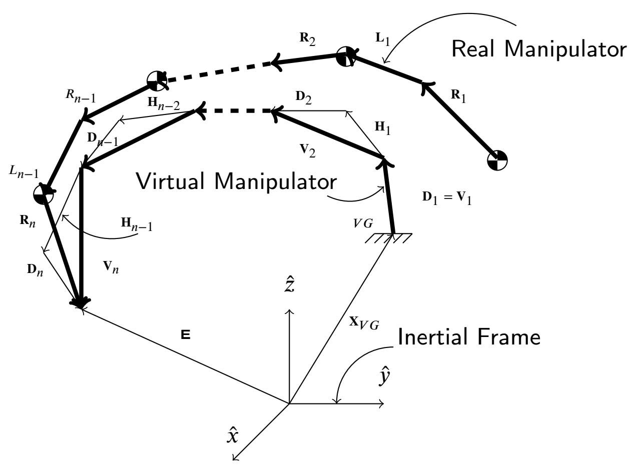

Figure 8: A free-floating manipulator and its corresponding virtual manipulator [87]

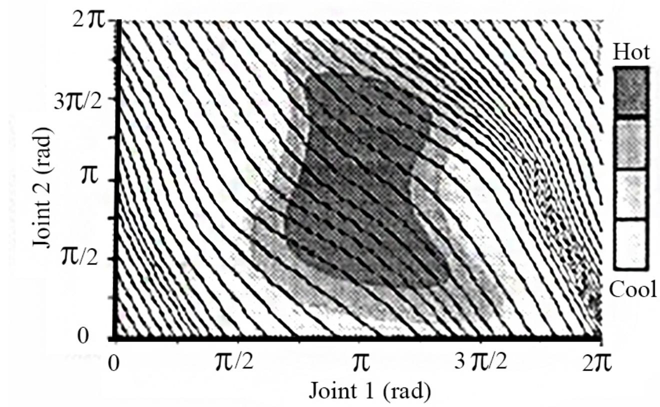

Figure 9: Enhanced disturbance map for a 2D robotic arm [86]

where

$$D_i = R_i \Sigma_{j=1}^{i} \frac{m_j}{m_{tot}}, \tag{38}$$

$$H_i = L_i \Sigma_{j=1}^{i-1} \frac{m_j}{m_{tot}}, \tag{39}$$

with R_i being the vector from the CoM of the i^{th} link to the next joint and L_i being the vector from the same joint to the CoM of the next link as depicted in Figure 8. Therefore, the position of the joints in the VM differs from that of the real arm, but the position of the end-effector in VM always coincides with the position of the real end-effector (p^I_{ee})[370].

$$p^I_{ee} = X_{VG} + V_1(\theta) + V_2(\theta) + ... + V_n(\theta). \tag{40}$$

Dubowsky and Papadopoulos use the VM concept to design linear controllers in the reduced phase space[266], and to investigate the dynamic singularities of free-floating space manipulators[261]. Parlaktuna and Ozkan use the VM concept to develop an adaptive control method in joint space for a free-floating space manipulator[269]. The VM is particularly useful for empirical testing by facilitating the setup of a fixed-base robot simulator equivalent to a free-floating one[185]. Torres and Dubowsky make use of the concept of virtual manipulator to develop the disturbance map[346]. They proposed a computationally efficient method of planning arm paths to minimize disturbances on the base spacecraft using manipulator redundancy[347]. They also demonstrated this method's capability to produce path-planning and control strategies that minimize the negative effects of the dynamic coupling between the arm and its moving base[86]. They develop a graphical representation for a 2D arm showing the motions that lead to maximum or minimum disturbances on base spacecraft at each point in the joint configuration space. Infinitesimal changes in the spacecraft pose can be expressed as a function of infinitesimal manipulator joint motion, using Equation 32. Since usually the orientation of the spacecraft is of higher importance, researchers mostly focus their attention to the infinitesimal attitude change of the spacecraft. The results of Dubowsky's solution can be also used as initial points for more accurate and more cumbersome numerical methods[347]. He also expanded the method from 2-DOF to multi joint systems [199, 346]. In the enhanced disturbance map, paths exist along which the disturbance to spacecraft is always zero or minimal. The map is used to find zero disturbance paths or paths that avoid regions of high disturbance in the disturbance map[346].

5.2. Base Spacecraft is Controlled (Free-Flying)

Free Flying spacecraft-arm systems are not fixed to the ground, but their orientation is kept controlled via means such as Control moment gyros, momentum wheels and thrusters. A noteworthy early concept of free-flying robots used to manipulate other objects in orbit is "ROBIN", developed by Bronez and Clarke for the International Space Station[52]. Another notable example of a free-flyer is the Engineering Test Satellite VII (ETS-VII) by NSADA of Japan that carries a 6-DoF arm and acts as a testbed for several GNC methodologies[402]. Such a system is not underactuated anymore. But, it consumes extra fuel to keep the telemetry link and reject disturbances. The dynamical equation of free-flying system is similar to what was presented in Equation 17. The model includes base control forces in addition to the arm control input, and the total momentum is not constant anymore. The spacecraft is controlled either via an entirely online AOCS system or one that only compensates small disturbances on the base. Ellery studied the kinematics and dynamics of a single arm free-flying spacecraft and the disturbances on its base[90]. Huang et al. took advantage of the motionless base of a free-flying spacecraft with online AOCS to design a discrete trajectory planner for its robotic arm in a similar fashion as a fixed-base robot[137]. Rybus and Seweryn investigated the differences between free-floating and free-flying spacecraft-arm systems[294] and studied trajectory optimization[306], application of Bezier curves for singularity avoidance[296], and capture maneuvers for both cases [294]. A free-flying system with some unactuated joints may still be controlled and stabilized[225]. Aghili et al. propose, design and model a reconfigurable 6-DOF manipulator on-board a controlled spacecraft for on-orbit servicing[21]. Their proposed arm changes configuration by locking and unlocking specific cylindrical joints[19] to match the requirements of various phases of a capture mission, i.e., (i) extending reach, (ii) improving obstacle avoidance, and (iii) switching from launch configuration to deployment configuration[214]. They also further demonstrate the performance of this design through simulation.

5.2.1. *Optimal Control*

Optimization techniques are incorporated for control of free-flying spacecraft-manipulators, as well[306]. Lampariello incorporates a nonlinear optimization and a look-up table to find the optimal control corresponding to a cost function representing the total mechanical energy of the manipulator [177]:

$$A = \int ((\tau_m^{\mathbf{tr}}(t)\dot{\theta}_m(t))^2 dt. \tag{41}$$

Proximity to the joint limits, in addition to being the constraints of the problem, can be also included in the cost function[178]. Aghili designed a coordinated optimal controller for the pre- and post-capture phases of a robotic mission to capture a non-cooperative target that generates optimal arm trajectories while controlling the base spacecraft[10, 6]. Seddaoui and Saaj developed an optimal path planning algorithm using the genetic algorithm for a free-flying spacecraft-manipulator system that exploits the controlled motion of the spacecraft to enhance the safety of the arm motion[304]

5.3. Use of Multiple Arms

A robotic arm's motion can be used to control the orientation of the base spacecraft or reject disturbances. The roots of this idea can be traced back to Vafa and Dubowsky's proposal to plan arm cyclic motions to reorient the base spacecraft[369], taking advantage of the coupling effects between the base and the arm. K. Yamada validated the idea by demonstrating that the base spacecraft's orientation can be changed in specific directions by having the arm go through a certain trajectory[395]· [396]. Suzuki and Nakamura expanded the idea by using a Bi-Directional approach to solve the non-holonomic path planning problem of a 9-DoF spacecraft-manipulator only through the actuation of the six DoF of the arm[234]. Schulz discussed a special case of orienting the base satellite through the arm's movement as it is approaching the target through specific V-shaped trajectories that brought the base to its initial orientation without the need to perform cyclic motions[300]. One way of taking advantage of this idea is to use multiple arms mounted on a single spacecraft to simultaneously perform a task with one arm and control the unwanted motion of the base with another one[271]. The general dynamical equation of a free-floating robot with N arms mounted on the base spacecraft, as formulated by Moosavian and Papadopoulos, is[224]

$$\begin{bmatrix} M_b & M_{bm} \\ M_{mb} & M_m \end{bmatrix} \begin{bmatrix} \ddot{\theta}_b \\ \ddot{\theta}_m \end{bmatrix} + \begin{bmatrix} C_b & C_{bm} \\ C_{mb} & C_m \end{bmatrix} \begin{bmatrix} \dot{\theta}_b \\ \dot{\theta}_m \end{bmatrix} = \begin{bmatrix} 0 \\ \tau_m \end{bmatrix} + \sum_{k=1}^{N} \sum_{j=1}^{n_k} {}^I J_j^{(k)^{\mathbf{tr}}} F_j^{(k)}, \tag{42}$$

where ${}^I J_j^{(k)}$ is the Jacobian corresponding to Body j of the k^{th} manipulator, n_k is the number of links in the k^{th} arm, and $F_j^{(k)}$ is the external force at Body j of the k^{th} manipulator[224]. Here, θ_m must include the degrees of freedom of all arms. Yoshida et al. developed a generalized Jacobian matrix for multi-arm spacecrafts similar to Equation 34[407].

$$J_g^{(k)} = J_m^{(k)} - J_b^{(k)} M_b^{-1} M_{bm}, \tag{43}$$

where $J_g^{(k)}$ is the GJM for the k^{th} arm, $J_m^{(k)}$ is the manipulator Jacobian for the k^{th} arm, and $J_b^{(k)}$ is the Jacobian corresponding to the contribution of the base motion on the velocity of k^{th} end-effector. Although $J_m^{(k)}$ is only a function of the joint parameters in the k^{th} arm, M_b and M_{bm} include the effect of other arms on the base and consequently on the k^{th} end-effector motion. Yoshida et al. based a torque optimization control methodology on this GJM formulation[408] and developed a stabilizing arm controller[406]. Moosavian and Papadopoulos also analyzed the kinematics of a multi-arm system, proposed two different approaches of formulating its kinematics and formed a Jacobian matrix that relates the velocity of the i^{th} link of the k^{th} arm to the motion of joints[223]. They proposed two different model-based controllers and a method based on transposed Jacobian[264] for synchronizing the motion of several arms to concurrently minimize the disturbance on the base and reach the target. The transpose Jacobian method simply uses the GJM to generate the control command [263]

$$\tau_m = J_g^{(k)^{\mathbf{tr}}} [K_p e^{(k)} + K_d \dot{e}^{(k)}] \tag{44}$$

based on a PD controller on the k^{th} end-effector pose error $e^{(k)}$. The positive-definite matrices K_p and K_d include the proportional and derivative gains, respectively.

Multiple arms can also be controlled in coordination to cooperatively perform a task[340]. GNC approaches have been developed to enable fixed-base multi-arm robots to handle a target in coordination[159], track a trajectory[150], navigate around complicated environmental constraints[399], match parts in assembly and control inflicted forces on a target[129]. In the context of space robotics, Zhao et al. developed a coordinated controller with zero internal forces based on the computed torque method and the GJM to reject the base disturbances on a free-floating underactuated spacecraft-manipulator system[422].

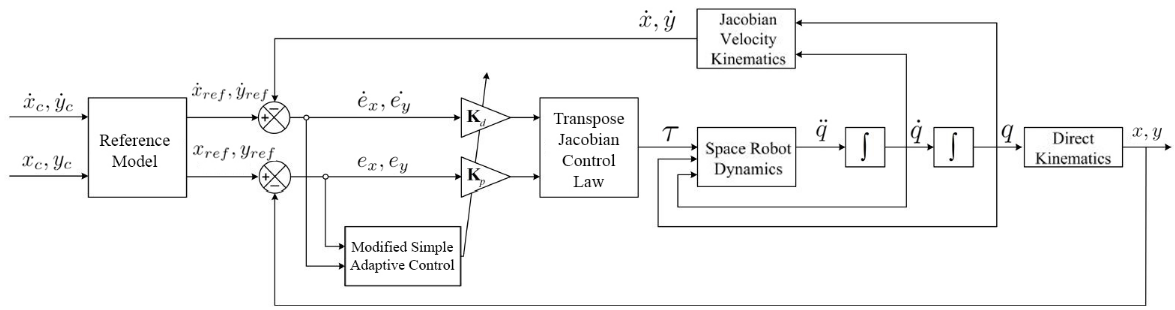

Figure 10: Configuration of a simple direct adaptive controller for a 2-link manipulator[356]

Yoshida et al. investigated coordinated control of multiple arms in space robots[406] to develop the concept of a stabilizing arm. Huang utilizes the secondary arm to balance the spacecraft while the main arm approaches the target[135, 134]. On the other hand, Shi et al. control both arms of the space robot to capture a single floating target in the presence of uncertainties[318]. Depending on the task, a multi-arm manipulator can benefit from a central decision-maker unit[118], a master-slave position/force controller[352] or a decentralized control logic[159, 158]. Yoshida et al. compared individual and coordinated control of dual arms mounted on a spacecraft[407]. The practicality of an automated coordinated control of dual arms has been experimentally demonstrated by Zhou[423].

5.4. Adaptive Control

Adaptive control schemes, due to their ability to adjust themselves according to external and internal changes, are beneficial in dealing with unknown environments and non-cooperative targets. Walker makes use of an adaptive controller to achieve stability despite the uncertainties in the dynamic and inertial parameters of a spacecraft-manipulator system[378]. Wang and Hanlei incorporate a generalized dynamic regressor in adaptive inverse dynamics study of a free-floating spacecraft-arm system to account for the nonlinearities due to unknown or varying parameters[379]. Wee et al. demonstrated the capabilities of adaptive control methods in controlling trajectories of a free-floating spacecraft and a 6-DOF arm simultaneously by having the adaptive logic acquire parameter estimations through momentum integrals[383]. Ulrich and Shi demonstrated an adaptive controller's ability to deal with large inertia uncertainties without the need for online estimation[317]. Ulrich et al. also developed a passivity-based output feedback adaptive control law to improve the stability and robustness of a path-planner for spacecraft-arm systems[354]. Less complex adaptive control logics are proven to be effective in controlling space robotic arms despite their simplicity[361]. Ulrich et al. evaluated the performance of a simple adaptive controller with the configuration shown in Figure10 [353]. Adaptive controllers operate on the basis of tuning the control gains based on feedbacks received from the output of dynamical systems. Ulrich et al. propose a Direct Adaptive Control (DAC) based on an output feedback transpose Jacobian control law [353] (Figure 10) for a sample 2-link manipulator:

$$\tau_m = {}^I J_{ee}^I(\theta)^{\mathbf{tr}}[K_p(t)e + K_d(t)\dot{e}], \tag{45}$$

where e is the end-effector position error. One adaptation logic suggested by Ulrich for their Modified Simple Adaptive Controller (MSAC) is[353]

$$K_p = (ee^{\mathbf{tr}}\Gamma_{pp}) + \int (ee^{\mathbf{tr}}\Gamma_{pi} - \delta_p K_{pi} I_{6\times6})dt, \tag{46}$$

and

$$K_d = (ee^{\mathbf{tr}}\Gamma_{dp}) + \int (ee^{\mathbf{tr}}\Gamma_{di} - \delta_d K_{di} I_{6\times6})dt, \tag{47}$$

where Γ_{pp}, Γ_{pi} , Γ_{dp} and Γ_{di} are control parameters adjusted by the designer and δ_p and δ_d are small positive control coefficients used to prevent the integral terms of the control gains from diverging[353]. Another common adaptive control approach, named Model Reference Adaptive Control (MRAC), includes a reference model and incorporates the output of the model x_m along with a scalar reference model input signal v_m in the overall control signal[355]

$$\tau_m = \begin{bmatrix} K_e(t) & K_{x_m}(t) & K_{v_m}(t) \end{bmatrix} \begin{bmatrix} e \\ x_m \\ v_m \end{bmatrix}, \tag{48}$$

and the control gains are adapted via

$$\begin{bmatrix} K_e(t) \\ K_{x_m}(t) \\ K_{v_m}(t) \end{bmatrix}^{\mathbf{tr}} = e \begin{bmatrix} e \\ x_m \\ v_m \end{bmatrix}^{\mathbf{tr}} \Gamma_p + \int e \begin{bmatrix} e \\ x_m \\ v_m \end{bmatrix}^{\mathbf{tr}} \Gamma_i, \tag{49}$$

where Γ_p and Γ_i are control parameters, and $K_e(t)$, $K_{x_m}(t)$ and $K_{v_m}(t)$ are gains corresponding to the error, system model output and model input, respectively[355].

Cao and Silva use Neural-Networks to aid their adaptive controller in path-planning for a space robot with flexible joints and links[56]. A closed-loop adaptive control requires a sensory system accompanied with a reliable state estimation. Ulrich and Sasiadek couple an EKF with an adaptive controller[358] to develop an adaptive feedback, feed-forward controller for a manipulator with elastic uncertainties at joints[362]. They demonstrate the adaptation capabilities of a direct adaptive fuzzy control to track the errors between a model and a real space robot[357]. Sasiadek and Green also apply a fuzzy logic system to adapt the gains of a transpose Jacobian controller in a flexible link robot[109]. Zhenyu Li proposes a self-tuning adaptive control scheme for free-floating space robots with unknown mass properties based on VM and least-square estimation technique[184]. Shibli, Su, and Aghili developed an adaptive controller based on the inverse dynamics of a free-flying space manipulator to perform contact operations[319].

5.5. Sliding Mode Control

A variable structure/hybrid type controller is able to switch between a gain set in the control law in response to system variations, resulting in resilience against disturbances and uncertainties[115]. The most well-known nonlinear variable structure control is Sliding Mode Control (SMC)[368]. SMC uses the state feedback to drive the system from its starting state to a sliding surface in the state-space, and it keeps the system in a narrow band neighboring the sliding surface via a switching control input always aiming towards the sliding surface[368]. A smooth control input tangent to the sliding surface ensures the system stability at an equilibrium point. Choice of the sliding surface and the control logic pushing the system to the sliding surface determines the behaviour of the controller. SMC, recently being investigated for space robotics applications, has been extensively discussed in the literature for controlling nonlinear systems and fixed-base robot arms[29]. Lin, Zhu and Cai presented a hybrid controller based on SMC for an underactuated 2-DoF robotic manipulator by breaking the system down into two sub-sliding surfaces[190]. Ashrafioun and Erwin developed a sliding mode control methodology for underactuated multi-body systems by defining the sliding surface as a linear combination of tracking errors of actuated and unactuated states[33]. They rearrange the dynamics of a free-floating space manipulator system defined by Equation 17[33] to attain

$$\begin{bmatrix} M_b & M_{mb} \\ M_{bm} & M_m \end{bmatrix} \begin{bmatrix} \ddot{\theta}_b \\ \ddot{\theta}_m \end{bmatrix} = \begin{bmatrix} f_b \\ f_m + \tau_m \end{bmatrix},$$

where f_b and f_m include the centrifugal and Coriolis effects, in addition to conservative and non-conservative forces. Solving for accelerations and introducing the sliding surface s as a linear combination of tracking errors of actuated states e_m and unactuated states e_b and their derivatives

$$\begin{aligned} s = \alpha_m \dot{e}_m + \lambda_m e_m + \alpha_b \dot{e}_b + \lambda_b e_b \\ =: \alpha_a \dot{\theta}_m + \alpha_b \dot{\theta}_b + s_r, \end{aligned} \quad (50)$$

the following control law is proposed[33]:

$$\tau_m = -\hat{M}_s^{-1}(\hat{f}_s + \dot{s}_r + k\mathbf{sgn}(s)). \quad (51)$$

Here, α_m, α_b, λ_m and λ_b are controller parameters determining the sliding surface, and $\hat{M}_s$ and $\hat{f}_s$ represent estimations of the model parameters M_s and f_s, some generalized mass matrix and force vector defined by Ashrafioun and Erwin[33]. The $k\mathbf{sgn}(s)$ is added as the chattering control input that aggressively pushes the system towards the sliding surface.

SMC remains an under-explored yet promising approach for the control of spacecraft-manipulator systems. Yinghong and Shijie developed a decentralized adaptive SMC for a specific form of space robots with 3-DoF joints and control moment gyros mounted at each joint[151]. Arisoy and Bayrakceken demonstrate the advantages of a high order sliding mode control for space robotic purposes by applying it to a single link flexible free-floating robotic arm[32] to exploit the robustness of the SMC in damping undesired elastic behaviour. Guo and Chen developed a robust terminal sliding mode control to concurrently control both a spacecraft and the end-effector of its arm[114]. Lu et al. utilize the concept of terminal SMC to develop (i) trajectory controllers for attitude synchronization of a chaser spacecraft with a tumbling target[394], (ii) robust, optimal attitude matching control in close-range approach[197], and (iii) coupled position and orientation control in direct docking to a target[196]. Saaj and Bandyopudhyay[39, 297] developed an easy-to-implement sliding mode controller for a discretized system using multi-rate output samples. They showed that the switching function and the control laws for such a system can be directly obtained from output samples of the control command.

5.6. Considering Arm Flexibility

One step towards bringing the dynamical model of a rigid multi-body system closer to reality is to account for the flexibility of the bodies[236] or the joints. The dynamics formulation of a robotic arm with flexible joints, established by Spong[325], has been widely used by researchers[359]:

$$\begin{aligned} \begin{bmatrix} M_b & M_{bm} \\ M_{mb} & M_m \end{bmatrix} \begin{bmatrix} \ddot{\theta}_b \\ \ddot{\theta}_m \end{bmatrix} + \begin{bmatrix} C_b & C_{bm} \\ C_{mb} & C_m \end{bmatrix} \begin{bmatrix} \dot{\theta}_b \\ \dot{\theta}_m \end{bmatrix} \\ - \begin{bmatrix} 0 & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} \theta_b \\ (\theta_I - \theta_m) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \end{aligned} \quad (52)$$

where K is the constant diagonal stiffness matrix for the joints and θ_I is the vector of rotation angles corresponding to the actuators' shaft. The input command vector τ_m enters in the coupled dynamics of the elastic joints[359]

$$J_I \ddot{\theta}_I + K(\theta_I - \theta_m) = \tau_m, \quad (53)$$

where J_I consists of the actuators' inertia. Identification of the elastic characteristics of a body is a complex task of its own[175]. Kumar controlled the trajectory of a 2-DOF chaser-arm system modeled as two Euler-Bernoulli beams via bond-graph modeling[176]. Ulrich and Sasiadek[361] model their flexible spacecraft-arm system via a third order polynomial for flexibility coefficients. They also investigate capabilities of four control approaches in dealing with flexible-joint robot arms[359]: (i) Slotine and Li (SLI) control, consisting of a PD controller and a full dynamics feedforward compensation term[324], (ii) Spong's expansion of SLI, called singular perturbation-based control[326],

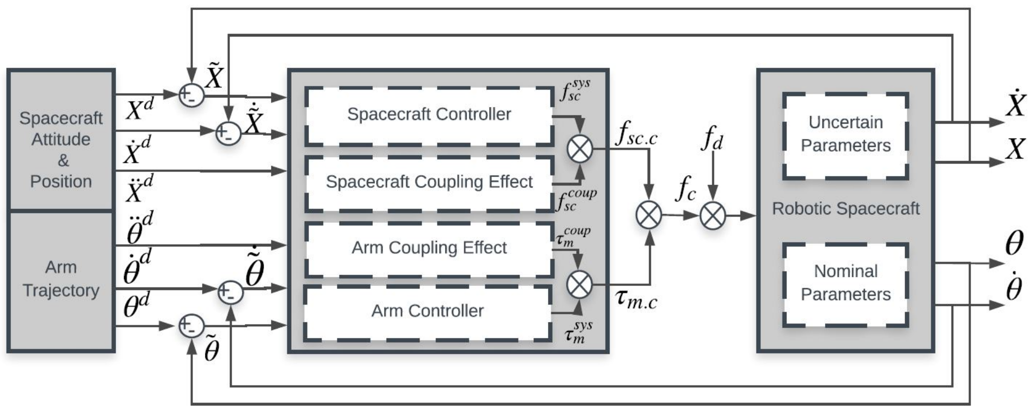

Figure 11: A robust H_∞ control architecture[303]

(iii) Brogliato, Ortega and Lozano's proposed nonlinear backstepping control approach[51], and (iv) PD control . Murotsu studied the effects of flexibility on the control of free-flying systems and categorized several path planning methods, including use of (i) a local PD-control, (ii) a virtual rigid manipulator, (iii) a pseudo resolved acceleration control, (iv) a Linear Quadratic Gaussian (LQG) control applied to the modal formulation of arm dynamics, (v) a composite pseudo resolved acceleration control, and (vi) a modal control minimizing the vibration at the links[230]. Nanos aggregates the effects of link flexibility and joint elasticity at harmonic gear mechanisms and introduces the equivalent stiffness at the joints[237]. Dubanchnet in his PhD work derived dynamic models, path planning and closed-loop control schemes for flexible manipulators and demonstrated the robustness of his proposed method through hardware-in-the-loop experimentation[83]. Adaptive and learning schemes such as neural networks are particularly beneficial to the control of robots with flexible linkages, due to their complex and often unpredictable dynamic behaviour. Newton and Xu implement a recurrent neural network architecture to improve the control performance of a space manipulator, and compared their results with a simple PID controller[244].

5.7. Robust Control

Robustness against internal and external disturbances is critical when controlling a spacecraft-arm system in orbit, since slight deviations may damage the system or the target and in drastic situations may result in collision and generation of debris[182]. Although robustness of manipulator path-planning is a recurring objective in the literature, direct robust controllers are not commonly utilized. Aghili and Su designed a robust relative navigation system through application of ICP and AKF algorithms using a laser scanner and IMU that was proved to be robust against harsh lighting conditions[22]. Dor and Tsiotras studied application of ORB-SLAM in a non-cooperative rendezvous problem, and demonstrated its robustness against spacecraft rotational perturbations disturbing pose estimation[82]. Many sliding mode and adaptive controllers also demonstrate disturbance rejection capabilities[197, 4]. A robust control scheme is often a form of optimal control whose objective function represents the effects of disturbance and uncertainty on the output. The nonlinear H_2 and H_∞ controllers are well-known for their robustness against internal and external disturbances[301]. H_∞ controllers were developed in 1994 by Johansson based on quadratic optimization of motion control[153] and their improvement to reject disturbances was proposed by Chen et al. [61]. The method was tested for a fixed-base robotic arm[61], and used for air and spacecraft attitude control, since they face considerable external disturbances[398, 351]. H_∞ is an optimal control scheme where the controller is designed to confine the infinity norm of the disturbance effects on the system output. Recent attempts have been made to use a combination of H_2 and H_∞ methods to control flexible joint manipulators[257] in order to prevent the actuators saturation. Simulations performed by Saaj and Seddaoui demonstrated robustness against perturbations and stability of combined feedforward/feedback compensation based on a nonlinear H_∞ scheme for concurrent control of arm and spacecraft base[303]. They also demonstrate capabilities of linear controllers such as PID, feedforward and LQR methods in OOS missions[222] . Figure 11 shows their control architecture. In a more recent study, they also proposed a robust H_∞ control law to compensate for the disturbance effects during a space manipulator operation, caused by internal dynamic coupling, changes in mass, or external disturbances[301]:

$$\begin{bmatrix} \tau_b \\ \tau_m \end{bmatrix} = -R^{-1} B^{\mathbf{tr}} T_0 \begin{bmatrix} e_b \\ e_m \end{bmatrix}, \tag{54}$$

where B is the input matrix, R and T_0 are the tuning matrices in the optimization process satisfying the following Riccati equation. As before, e_b and e_m are the tracking errors for the base and the manipulator, respectively.

$$\begin{bmatrix} 0 & K \\ K & 0 \end{bmatrix} - T_0^{\mathbf{tr}} B (R^{-1} - \frac{1}{\gamma_d^2} E) B^{\mathbf{tr}} T_0 + Q = 0, \tag{55}$$

where both K and Q are weighting functions and γ_d is the attenuation level, which is a constraint on R found from Cholesky factorization[301].

Siquera performed a comparison study of robustness of concurrent controllers using H_2 and H_∞ schemes, their combination, and the method of μ-synthesis applied to underactuated systems[323]. This comparison proved μ-synthesis the most robust method while being computationally the most expensive one, and H_2 the least robust method of control. Another demonstration of robust performance of H_2 control was performed by Lee and Mavroidis, who synthesized an H_2 control via LQR method to reject perturbations caused by handling flexible payloads[180]. Dabuchnet et al. implemented a fixed H_∞ logic for rejecting disturbances while tracking a grasp point on a target using a PD controller[84].

6. GNC for Capture and Post-Capture

As the end-effector impacts the target the arm will experience a significant reaction force that is also transferred to the chaser spacecraft. The undesired effects of this reaction should be minimized or controlled. In addition in post capture phase, the chaser and the target act as a unified dynamic object whose inertia and other dynamical parameters should be determined. Maneuvers should be planned to reorient, de-tumble, move or mitigate the target. If the target is non-cooperative, a common first step is to damp the motion of the target to stabilize the trajectory of the system and avoid any collision between parts.

6.1. GNC Considerations in capture Phase

Two approaches are common in dealing with the reaction forces upon impact: (i) absorbing the impulse through force control methods or structural damping , and (ii) minimizing the impact force via proper choice of the contact point and well-designed pre-impact trajectories. Impedance control, as proposed by Yoshida et al., is an example of the former approach, which was introduced for capturing and controlling the dynamics of an uncontrolled target[409]. It incorporates an analytical mass-spring-damper model, minimizes the impact force, and provides a criterion to maintain contact or push the target away[409]. Yoshida et al. formulated the contact dynamics between two free-floating bodies[410] using virtual masses and a spring at the contact point. The spring constant (impedance) is a function of the manipulator configuration, which will be adjusted to introduce a desired impedance at contact. Pre-impact configuration can be planned so that the impact will not change the angular momentum of the robot[242]. Directions of the impulsive force that transfer minimal impact momentum to the base are studied by Nenchev and Yoshida[242]. They extend these findings and use RNS to facilitate arm control in post-capture maneuvers[240]. Cheng, Tianxi and Yang introduced a grasping strategy based on the concept of dynamic grasping area to study the effects of grasping control parameters and mass distribution[63]. Through experimentation they showed that the reaction forces can be noticeably

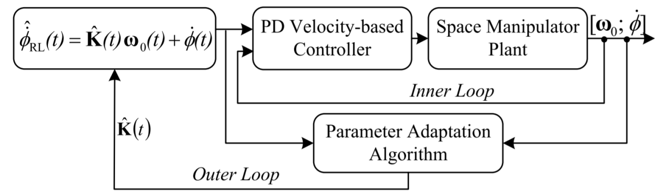

Figure 12: Architecture of an adaptive controller for transition phase[246]

reduced, by carefully adjusting the control parameters while considering the impact speed of the arm. Elastic properties of the links become crucial at the capture instant as the elastic DoF of the arm are excited upon impact. Liu, Wu and Lu investigated the elastic behaviour of two flexible arms in post-capture in the controlled and uncontrolled cases[192].

6.2. System Identification after Capture

On-line parameter identification is crucial when manipulating a non-cooperative target, since (i) the exact dynamic properties of the target are not known a priori, (ii) the impact might cause deformations in the target, and (iii) the motion of the chaser and the target are coupled after capture. Identification procedures typically work on the basis of kinematic motion of the chaser or the torque/force between the end-effector and the target. The inaccuracies in the target model often result in unexpected tumbling motion immediately after capture, causing the controller to perform poorly. On-line adaptation techniques have been proposed to minimize the effect of these inaccuracies. Abiko transfers motion of the target to momentum wheels on-board the chaser, using the coupling between force and momentum in an adaptive control law[3]. Murotsu et al. present another approach that uses the conservation of momentum to identify the coupled dynamics and inertia tensor of the chaser-arm-target system when only one joint of the manipulator is driven[229]. Partitioning the system into three rigid bodies, they form the (linear) relation between the target inertia parameters (10 variables) and the measurable parameters of linear velocity of the target and angular momentum of the chaser-arm before capture (6 variables) by setting the total linear and angular momentum of the chaser-arm-target zero. Generally, the fundamental equation used for identification is indeterminant and more than one data set or movement of more than one arm join is required to perform the identification. Murotsu, in the same line of research, discusses another approach including use of the Newton-Euler equations to estimate the system parameters[229]. Rackl proposed a torque-based post-grasp identification approach that can be utilized independent of knowing the base acceleration[282]. Nguyen and Sharf present a temporary identification logic and an adaptive reactionless controller to minimize the unfavoured effects of uncertainties in the transition between the capture and post-capture identification[246].

6.3. Post-Capture Control

The dynamics of the overall chaser-target system is affected by the capture phase. Cyril et. al formulated the overall system dynamics before and after capture through the use of an impact model to identify the change in the generalized velocities of both bodies[75]. They also investigated the extent of influence of the arm flexibility on smoothness of the impact, post-capture dynamics, and control performance[76]. Many pre-capture approaches are applicable to post-capture control. Specifically, adaptive control laws can be advantageous via remediating uncertainties in the target model estimation[245]. For example, Nenchev and Yoshida propose the same reaction null space concept used for disturbance minimization in pre-capture to analyze the dynamics of the impact[241]. Yoshida and Dimitrov propose an orthogonal decomposition of the joint space to analyze the post-capture behaviour, transfer the undesired target motion to the chaser's AOCS, and perform motion planning for post-capture[79]. They also propose the concept of preloading bias momentum in a space robotic system to enhance the capture and post-capture behaviour[79]. Reconfigurable control logics that are used in case of loss of thrusters or actuators are also capable of providing global asymptotic stability in the presence of model uncertainties after unification of the robotic system with an unknown target[133]. Nishida and Yoshikawa developed a joint virtual depth control approach to brake the target and relieve the impact load to the chaser[320]. They also proposed a joint compliance control and adding buffers to the end-effector to minimize the undesired effects of impact[247]. Sharf et al. developed two rigidization techniques to redistribute the momentum of a tumbling target after capture: a proportional-integral control and a redundancy resolution control [311].

6.4. Impedance Control

It is particularly beneficial to utilize force-based control schemes instead of state-based controllers when contact is involved. Such methods include impedance control, admittance control or compliance control. Resilience in control is vital in this step since large forces can disrupt the mitigation process. Therefore, Hirano, Kato and Saito present online robust path planning algorithms based on compliance control for a spacecraft-arm system to particularly handle large tumbling targets[121]. Impedance control is a commonly used method to damp the undesired motion of a non-cooperative target[366]. It includes adding dynamic elements such as spring and damper at joints to control the forces encountered by the arm[411]. The contact is often modelled as an impedance of its own. Uyama, Yoshida, Nakanishi and Nakaoga propose an impedance-based contact control algorithm that tunes the impedance parameters to obtain a desirable damping and coefficient of restitution (ratio of the final to initial relative velocity of spacecraft and target)[367]. The impedance control law is defined as

$$M\,{}^I\ddot{p}^I_{ee} + C({}^I\dot{p}^I_T - {}^I\dot{p}^I_{ee}) + K({}^Ip^I_T - {}^Ip^I_{ee}) = -f_c, \quad (56)$$

where f_c is the contact force, and M, C and K are mass, damping, and stiffness coefficients of impedance control,

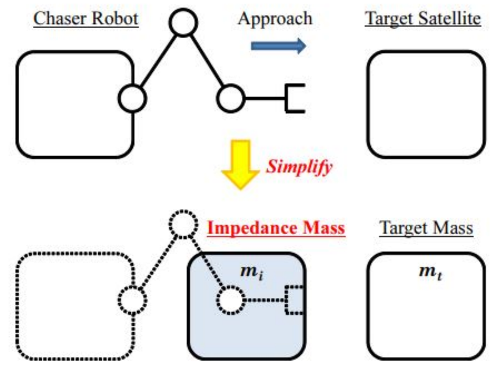

Figure 13: Lumped impedance at contact point for impedance control[411]

and ${}^Ip^I_{ee}$ and ${}^Ip^I_T$ are the position of the end-effector and a grasping point on the target with respect to and expressed in the orbital inertial coordinate frame. Practical advantages of compliance control for handling of contact dynamics have been demonstrated via novel simulations performed by Palma and Seweryn [259]. Use of multiple Impedance control for servicers with multiple arms that manipulate a single target has also been explored by Moosavian, Rastegari and Papadopoulos[1].

6.5. Flexibility of the Target

Not only the structural flexibility of the chaser-manipulator system, but also that of the target object affects the overall dynamics of the chaser-target system, which is critical at the moment of capture and in post-capture maneuvers. Ishijima et al.[144] investigated the use of a free-flyer to manipulate a flexible space structure incorporating a modal active damping control law to suppress unwanted vibrations and maneuver the payload via the chaser's thrusters, similar to a rigid body. Another example of handling flexible targets with space manipulators occurs in the task of assembly. Boning and Dubowsky[49] propose that a team of space robots assemble large space structures in orbit. This heavily complicates the dynamical modelling and collaborative control of the robotic team, since various flexible modes of the structures are excited in the assembly process. Gasparri and Pisculli[104] present two optimal flexibility compensation approaches for capture and post-capture phases when a space robot equipped with two flexible arms interacts with a flexible target.

6.6. Optimal Control

Similar to pre-capture phase, there may be certain criteria that must be optimized in post-capture motion planning. In such situations the target dynamics is often described as free-floating rigid body dynamics (Euler Equation 8)[7]. The goal is normally to bring the target satellite to rest and move it to a specific location in minimum time, considering a torque limit τ_{max}. As Aghili suggests, the following cost function should be minimized for a de-tumbling maneuver[6, 7]:

$$A = \int_0^{t_f} 1 dt, \tag{57}$$

subject to the constraints $\omega_T(t_f) = 0$ and $\|\tau\| \leq \tau_{max}$. Then theory of optimal control dictates that the time-optimal torque history (τ^*) is

$$\tau^* = -\frac{I_T \omega_T^*}{|I_T \omega_T^*|} \tau_{max}, \tag{58}$$

where ω_T^* satisfies

$$\dot{\omega}_T^* = -I_T^{-1}((\omega_T^*)^{\times}(I_T \omega_T^*)) - \frac{\omega_T^*}{\|I_T \omega_T^*\|} \tau_{max}. \tag{59}$$

They have recently extended their pre-capture optimal control methods further for post-capture applications of tumbling targets[11]. Wang et al.[381] also propose an optimal strategy for detumbling a captured target based on quadratic Bezier curves and adaptive particle swarm optimization algorithm.

7. Prospective Vision of GNC Techniques

In this section, two families of emerging control approaches based upon reinforcement learning and geometric mechanics are studied and their application to the GNC of space robotic systems is briefly explored. The capabilities of each approach in enhancing existing GNC systems or solving their shortcomings are emphasized in the sequel subsections.

7.1. Reinforcement Learning

Long-term autonomy necessitates the incorporation of machine intelligence in the GNC technologies designed for space robots to adapt to changes in their physical components, environment, or mission requirements[235]. Artificial Intelligence (AI) offers an alternative approach to the GNC design by including goal-based planning, self/environment perception, learning/training, reasoning, pattern recognition and adaptable mission execution[272]. One of the primary goals behind converging AI and robotics is to optimize the level of autonomy through learning, which provides the capability to predict the future, either in planning a task or interacting with the surroundings. Machine Learning (ML) is currently at the core of research and development in AI and autonomy. From the three main streams of ML, being supervised, unsupervised and reinforcement learning, the last one is the most suitable for GNC applications. Reinforcement Learning (RL) is typically used in robotics for adapting control laws to reject modelling flaws or disturbances. RL is incorporated in various control schemes including adaptive, robust, or simple PID to enhance the performance of trajectory planning and control for earth-based robotic arms[92, 187, 254]. Originally, observation of optimal behaviour in nature motivated research on RL as a computational means for learning from environmental interactions. These interactions involve assessing the quality of a taken action in terms of reward or punishment. RL techniques can work off-policy and develop their own system/environment models[111], which make them attractive for use in systems dealing with unknown or changing environments, lacking comprehensive self models, or facing considerable internal or external disturbances. Recently, a robot with RL-based control logic that had been entirely trained in a virtual environment was successfully migrated to the physical world[194]. Training in virtual environment not only can be faster and safer, but it also results in control policies with more resilience against modelling errors and uncertainties in system identification[331]. Model-based RL includes planning that is sensitive to modelling bias[276]. RL can also improve closed-loop control performance of nonlinear systems as Bhasin investigates in his thesis[44]. He develops a robust adaptive controller with an actor-critic architecture that can deal with disturbances. Senda et al. improved on-line performance and computational efficiency of their space robotic simulator via RL[305]. Considering the need for autonomy and the unknown nature of non-cooperative targets in many OOS missions, RL can significantly boost the performance of available control schemes to improve the GNC of a servicer spacecraft in orbit. The existing RL algorithms are not yet ready to be practically implemented in space systems[167]. The model-free RL approaches require a large number of exploratory trials to find optimal policies, although space systems have limited resources. Further, current RL algorithms often work better in low-dimensional dynamical systems, and they may push robotic systems into unstable regions or unsafe contact if not tuned carefully[167]. Therefore, a practical learning method must be based on a model that captures modularity, constraints, environmental interaction and nonlinearity of space robotic systems. Although learning provides the best outcome when the hardware interacts with real environment, for safety reasons, the learning process should also involve some simulation aspects[200] to avoid catastrophic harm to robots and our assets in orbit. Table 2 summarizes the available tools that reinforcement learning provides to develop advanced GNC technologies for different phases of in-orbit robotic missions.

7.1.1. Path-Planning

Although RL-based controllers typically work with a discrete model of the environment, called Markov Decision Process (MDP), they can contribute to continuous problems through: (i) facilitating path-planning of a robot in its configuration space that is discretized via a Probabilistic RoadMap (PRM)[268, 94] or a Cerebellar Model Arithmetic Computer (CMAC)[117, 164], and (ii) an actor-critic algorithm [186]. Actor-critic approaches are further discussed in section 7.1.4. The configuration space of an arm is represented as a Cartesian space, e.g., for a planar fixed-base arm with two joints it is a 2-D Cartesian space in Figure 14. Obstacles that are observed in the surrounding environment can be mapped to the configuration space[268]. If this map is com-

Table 2
Potential RL-based GNC methodologies for space robotic applications

GNC Method	Petential Applications	Advantages	Disadvantages
Q-Learning	- Identifying orbital disturbances - Identifying uncertain space manipulators in pre-capture - Identifying target during post-capture phase	- Being the base for other RL methods - Identifying uncertain systems in real-time - Rejecting noise and disturbance - Enabling robot self-assessment	- Requiring numerous trials - Being suitable for discrete system models - Maybe leading to unsafe system configurations
Probabilistic Roadmap (meshing)	- Collision-free arm path-planning - Minimum-disturbance arm path-planning - Concurrent spacecraft/manipulator path-planning	- Being computationally efficient - Being compatible with discrete learning methods and controllers - Avoiding dynamic obstacles - Adapting to changing environment	- Generating sub-optimal trajectories - Generating discontinuous commands
Cerebellar Model Arithmetic Computer	- Similar to PRM method	- Being compatible with discrete learning methods and controllers - Requiring less exploration relative to continuous and full meshing algorithms	- Roughly estimating the system - Performing unevenly in different parts of the environment - Having slow real-time performance
Actor-Critic	- Facilitating augmented adaptive control of space manipulators - Tuning controller in real-time in post-capture phase - Identifying target in real-time - Rejecting orbital disturbances in the arm's GNC	- Being directly applicable to continuous space manipulator control - Adapting and identifying the environment and uncertainties in real-time	- Being computationally intensive - Requiring complex hardware and testing

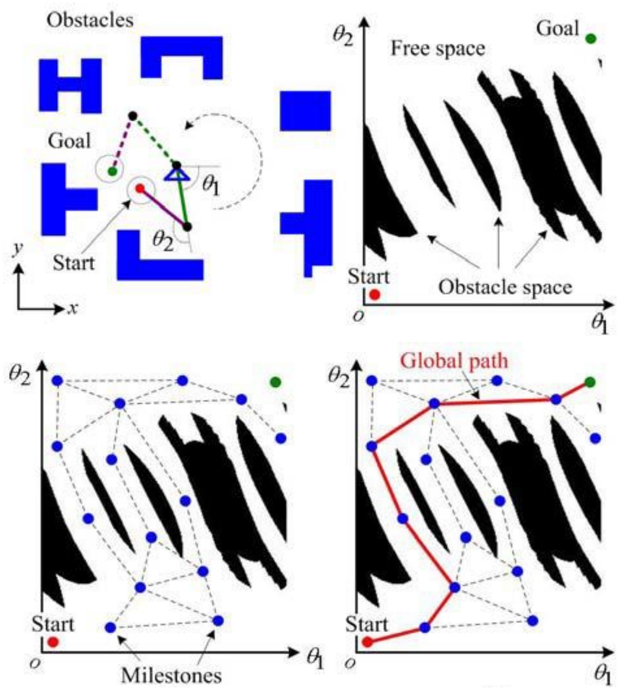

Figure 14: Generation, discretisation and search in configuration space for a 2-link robot using PRM[268]

plete, RL can generate a collision-free path for any desired start and end point[220]. As mentioned, RL can be fused with other path-planning methods, such as PRM[94]. In the pre-process phase, PRM generates a set of random points in admissible regions of the configuration space, which are called nodes or milestones. In the query phase, these nodes are connected by legs to form a grid, called the RoadMap (RM), where the robot can navigate without colliding the obstacles. Figure 14 portrays the workspace of a 2-DoF fixed-base arm that is mapped into its configuration space. The configuration space is then discretized and the RM is formed from the generated nodes. A global semi-optimal path is then generated in that RM[268]. The generated path by this method may not be the globally optimal path, but it is a good approximation in the favour of reducing the computation burden. As the result, the method is suitable for real-time application in GNC systems. A learning or optimization algorithm, such as RL[268] and Q-learning[421], is typically coupled with PRM[164, 38]. In an RL procedure an agent at a certain state s with the value $V(s)$ chooses an action a with an action-value $Q(s,a)$ that with the probability $P(s,s')$ leads to the next state s'. It observes the reward ρ from that target state and action, and repeats the same process to move in the environment. After going through several cycles from start to terminal states and updating the values of the states based on the observed rewards, the algorithm converges to an optimal policy π (control) to guide the system through the environment. A state s is a certain configuration of the arm with the state value V assigned to it. The action a can be considered to be the joint velocities that drive the arm from state s to state s'. The function V is updated through the expected value of the action-values Q for different actions taken at the state s following policy π. The function Q is then updated by the sum of the expected returns via choosing a certain action a at a certain state s[335].

$$V_\pi(s) = \mathbb{E}_\pi[G_t|s_t = s, \pi], \tag{60}$$

$$Q_\pi(s,a) = \mathbb{E}_\pi[G_t|s_t = s, a_t = a, \pi], \tag{61}$$

where G_t (return) stands for the accumulated reward following the policy π after step t. Different RL algorithms use various update rules for V, Q and their respective learning methods. Park et al. investigated different RL methods such as Monte-Carlo, Q-learning, simple Temporal Difference (TD) and Dynamic Programming (DP) for arm path-planning and suggested Q-learning due to its balanced behaviour in exploration and exploitation of the grid [268]. They incorporate image processing to observe the changing environment, obstacles and workspace and form a PRM.

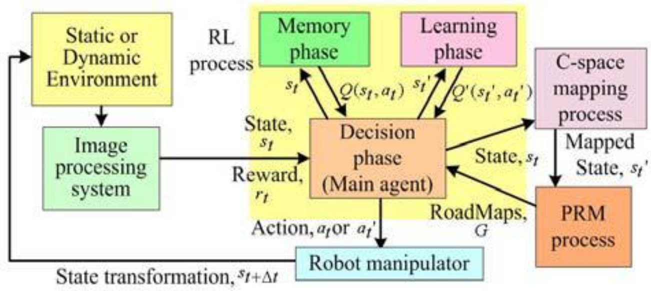

Figure 15: Workflow of an RL-PRM controller coupled with visual techniques[268]

A Q-learning agent commands arm's motion in PRM, evaluates its states, learns and updates the control logic. Q-learning uses the following formulation to update its action-value in the learning phase.

$$Q(s_t, a_t)^{k+1} \leftarrow (1-\alpha)Q^k(s_t, a_t) + \alpha(\rho_t + \gamma \max_a Q^k(s_{t+1}, a) - Q^k(s_t, a_t)), \quad (62)$$

where the subscript t refers to parameters at time step t, γ is the discount factor that defines the extent that the algorithm looks into the future, and α is the learning rate. Normally, a Q-learning agent moves based on an ϵ-greedy policy, but updates Q based on the actual best path (greedy solution) at each node, ensuring exploration of the environment while mostly following the optimal path (exploitation). In a ϵ-greedy policy, The agent follows the optimal path at $(1-\epsilon) \times 100\%$ of times and randomly explores the environment at $\epsilon \times 100\%$ of times.

7.1.2. System and Environment Identification

Reinforcement learning algorithms can generate MDP or continuous models to capture the behaviour of a system or the environment. Even off-line methods (not real-time) such as Monte-Carlo can incorporate a Dataset Aggregation (DAgger) algorithm to identify the surroundings[338, 289]. Environments that are not completely observable can be also estimated via partially observable Markov decision processes, which demonstrate optimal behaviour achievable via on-line adaptive control[181]. RL Demonstrates a strong performance in on-line system estimation without requiring a pre-determined model compared to model-predictive control.[92] . Hwang, Tan and Tsai demonstrate that RL can capture the nonlinearities in an environment and effectively linearize it via building and adjusting a neural network[142]. They also prove the method's independence of system model and capability to perform estimation while controlling the system[142]. Fisac et al. incorporate an off-line rough estimation of the environment in an on-line learning logic to ensure safety while the algorithm learns about the system[96]. Model-based identification techniques include pre-defined models that are matched and tuned by RL to represent the environment. Ross and Bagnel developed and implemented a system identification approach using an on-line model-based RL to achieve near optimal control policies for unknown environments[289]. Pane provides another on-line system identification method using RL and actor-crtic logics for a robot whose physical properties unpredictably change in time[260]. An RL-based controller can simultaneously identify a system model, indirectly control it, adapt to the changes in the system/environment, and optimize a cost function[181]. Target identification is another phase of an in-orbit robotic mission that can significantly benefit from RL methodologies[220].

7.1.3. Applications to Mobile Robotics

RL and actor-critic learning algorithms, due to their capability to reject modelling flaws, noise and external disturbances, demonstrate an aptitude in their application to the autonomy of mobile robotic systems[112, 170]. This has been proven through simulations and real-life experiments[103]. Ostefaw et al. produce a learning-based nonlinear model predictive control law using recorded information about a disturbed rover traversing a path[254, 255]. Mihelich utilizes an RL actor to assess an uneven environment for traversing and adjust a legged robot's robust controller by choosing gains from pre-defined sets[219]. Bernstein et al. improve real-time decision-making performance of an autonomous planetary rover's controller by making use of the decomposability of task space into weakly-coupled separate environment models[43]. Learning-based vehicle controllers have demonstrated the ability to autonomously account for external disturbances, input nonlinearities and model uncertainties[74].

7.1.4. Robot Self-Assessment and Adaptive Control

Methods based on temporal difference can be considered as diagnostic approaches that asses their environmental model and update their estimate, in contrary to Monte-Carlo methods that wait for the completion of a full episode to update their model. Actor-critic controllers can employ an Associative Search Network (ASN) to asses their understanding of the robot dynamics[189], assuring robustness against modelling errors. Eski et al. experimentally investigate the ability of artificial neural networks in analyzing the faults in the operation of a robotic arm[93]. An actor-critic logic can augment another controller to assess its performance and tune it throughout an operation. Pradhan and Subudhi develop an adaptive controller for a flexible arm that has a critic evaluating its performance[278]. They control a non-minimum phase, underactuated system with variable payload. An actor-critic logic along with a least squares eligibility trace adaptive memory method can facilitate the self assessment process by tracking the sources of errors and relating undesired dynamic behaviours to their cause[278].

Figure 16 shows how an actor-critic is added on top of a PD controller to adapt to the changing dynamics of a two-link flexible manipulator[278]. The output of the dynamics is updated and goes through a zero-order hold to be compatible with on-line connection to the controller. The actor-critic part of the controller is able to minimize the temporal differ-

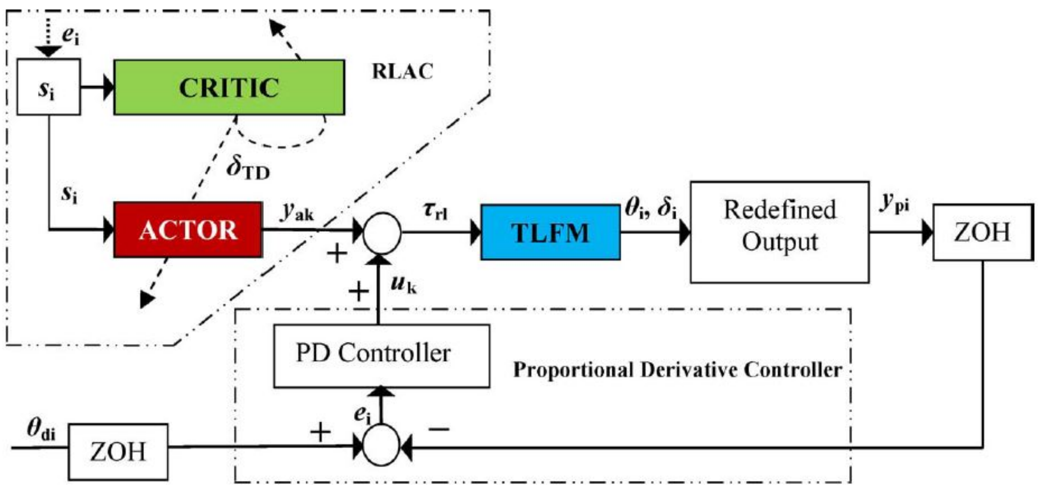

Figure 16: An adaptive controller augmented with an actor-critic evaluator[278]

ence error δ_{TDt}

$$\delta_{TDt} = \rho_t + \gamma \phi_{t+1}^{\mathbf{tr}} W_t - \phi_t^{\mathbf{tr}} W_t, \tag{63}$$

which is a prediction error. Here, the vector ϕ is the actor regressor and W is the matrix of the actor controller weights[278]. Adaptive neural control is another AI-based controller applicable to space manipulators through RL. Control actions can be generated by neural networks and the model accuracy can be assessed by a critic, which enables capturing of nonlinear effects[339].

Macnab and D'Eleuterio incorporate an artificial neural network and CMAC in an adaptive controller to improve performance while maintaining stability, through on-line updates of the weights in the control logic[198]. Lin employs another RL adaptive controller for a robot with an uncertain model, which includes an agent to collect signals from a fixed gain controller, an adaptive critic that evaluates the controller and a fuzzy action-generating element[188]. An adaptive controller for a manipulator employing RL is also able to directly identify the changes in the payload and accordingly tune the controller[334]. The concept can be employed in a similar manner to a space manipulator and assess the inaccuracies in the controller's model.

7.2. Geometric Mechanics and Control

Geometric mechanics is a branch of applied mathematics that studies nonlinear dynamical systems on their configuration manifolds that may or may not exhibit a Lie group structure. The methodology extensively incorporates tools in differential geometry to treat such complex systems in a coordinate-free manner. The configuration manifold Q includes all possible configurations of the system and the phase space consists of the required states to formulate the dynamics. For example, Lagrangian systems are described by the configurations and their velocities, i.e., elements of the tangent bundle TQ, and Hamilton's equation are defined based on the configurations and their conjugate momenta, i.e., elements of the cotangent bundle T^*Q. Therefore, dynamics of a regular system is a vector field on the phase space whose integral curve represents the time evolution of the system[226]. In the case of a rigid spacecraft-manipulator system, the configuration manifold of the system is of dimension $n+6$ and it is diffeomorphic to the set of all allowable relative transformations between the rigid bodies forming the system, which exhibits a Lie group structure.

The idea of reducing the phase space of a nonlinear system and accordingly its associated dynamics, initiated by Marsden and Weinstein[203] and K. Meyer[215], is at the core of geometric mechanics. Reduction can improve GNC methodologies by overcoming underactuation[377], dealing with non-holonomicity[46], enabling concurrent control, and allowing for switching between control laws[47], all of which are crucial in the GNC of space manipulators. Specifically in proximity operations, these free-floating systems are underactuated and non-holonomic due to the existence of an uncatuated base resulting in the conservation of momentum. They have to concurrently control the end-effector and the base to re-establish telemetry link upon completion of task execution. Since an in-orbit space robotic operation consists of several phases, they benefit from smooth switching control strategies[392]. Researchers have been able to demonstrate the above-mentioned advantages for real-life mechanical systems by exploiting geometric properties of robots[37, 128, 228], vehicles[336], manipulators[279] UAVs[123] and multi-body systems[226]. Müller and Terze provide an extensive overview of the potential applications of geometric modelling and control to multi-body systems[226]. Table 3 summarizes the provided approaches by geometric mechanics that can contribute to the development of advanced GNC technologies for different phases of in-orbit robotic missions.

7.2.1. *Symmetry and Dynamical Reduction*

A symmetry group of a geometric object is the group of all transformations under which the object remains

Table 3
Potential geometry-based GNC methodologies for space robotic applications

GNC Method	Potential Application	Advantages	Disadvantages
Dynamical Reduction	- Including nonzero momentum in free-floating regime - Generating trajectories for concurrent manipulator/base motion in pre-capture phase - Designing adaptation laws using reconstruction equations in post-capture phase - performing partial feedback linearization in reduced phase space	- Removing dependency on unactuated DoF of the spacecraft - Dealing with non-holonomic control problem of space manipulator motion - Providing robustness against sensory noise in the reduced DoF of the spacecraft - Providing accurate analysis platform	- Challenging implementation - Being prone to modelling uncertainties due to complexity of the reduced dynamics - Not being applicable to externally disturbed systems and free-fliers
Optimal Control	- Non-holonomic path-planning and optimal control in pre-capture phase - Providing optimal guidance laws for attitude synchronization phase - Providing optimal approach in orbital environment	- Rigorously implementing calculus of variation resulting in innovative solutions - Dealing with the non-holonomic and underactuated nature of space robots	- Challenging implementation - Not being robust to system/target uncertainties or orbital disturbances - Being numerically cumbersome
Geometric Partial Feedback Linearization	- Concurrently controlling base and end-effector in pre-capture phase - Studying zero dynamics and relative stability in pre-capture phase	- Providing tools for singularity analysis - Deal with non-holonomic and underactuated systems - Handling outputs on manifolds	- Challenging implementation - Requiring accurate system model
Geometric Robust and Adaptive Control	- Rejecting external disturbances in the arm end-effector control in pre-capture phase - Identifying target and offering global adaptive control laws in post-capture phase	- Enhancing numerical stability due to integration on manifolds - Removing unnecessary singularities due to parametrization	- Challenging implementation - Being too slow in transients

invariant[172]. For a dynamical system, symmetry is defined as the action of a Lie group G on the phase space of the system that leaves the dynamics vector field invariant. If the system is constrained, the Lie group action will also preserve the constraints of the system. Based on Noether's theorem, any continuous symmetry of the action functional in Hamilton's principle corresponds to a conserved quantity, called momentum map, along the trajectories of the system[80]. In the presence of symmetry, differential geometric techniques can be used to formally project the equations of motion of a system to a submanifold of its phase space through quotienting the symmetry group[285]. For example, the trivial behaviour due to the (not necessarily zero) momentum conservation of a multi-body system is eliminated via reducing its phase space to the cotangent bundle of the shape space of the system ($T^*(Q/G)$)[66]. The symmetry reduction procedure can be divided into three steps: (i) restricting the dynamics to a constrained submanifold of phase space, (ii) quotienting the constrained submanifold by a group action, and (iii) identifying the quotient manifold with a cotangent bundle[69]. This procedure is common among non-holonomically constrained and unconstrained mechanical systems.

The symplectic reduction theorem[203] made a historic impact on the unification of multiple reduction methods developed for Hamiltonian and Lagrangian systems, such as the classical Routh method and the reduction of Lagrangian systems by cyclic parameters[290, 204]. Using the symplectic and Poisson structures of the cotangent bundle, many reduction theories have been developed, such as the ones reported in [205, 45, 173] for Hamiltonian systems and in [58, 207, 206] for their Lagrangian counterpart. For systems with non-holonomic constraints whose dynamics is formulated through Lagrange-d'Alembert or Hamilton-d'Alemebert equations, reduction by symmetry is dated back to the work of Chaplygin[60]. He eliminated the Lagrange multipliers in Lagrange-d'Alembert equation and expressed a non-holonomic system in a reduced phase space using cyclic parameters of the system. His result was extended by Koiler to include non-abelian group actions in the reduction process[169]. Other reduction theories for non-holonomic systems with symmetry are reported in Hamiltonian or Lagrangian formalisms. In [46] a reduction method is introduced that is centred at defining a non-holonomic connection and a non-holonomic momentum map. The analogue of this approach using Poisson geometry is also explained in[45], which evolved from a paper by van der Schaft and Maschke[299]. Other forms of reduction of non-holonomic systems with symmetry can be traced in the works of Bates and Śniatycki[40], Gay-Balmaz and Yoshimura[105], and Ohsawa et al.[251]. Chhabra et al. discuss a geometric technique to reduce Hamilton-d'Alembert equation for multi-body systems with multiple non-holonomic joints[66]. They also present a geometric approach to the dynamical reduction of a class of symmetric mechanical systems with affine non-holonomic constraints[69]. Their approach unifies existing reduction procedures for Chaplygin systems and symmetric Hamiltonian systems with conserved momentum, which normally have distinct reduction procedures.

Reduction of dynamical systems has been proven helpful in studying their inherent behaviour, as well as in designing GNC systems. Sreenath developed angular momentum-preserving control laws using symplectic reduction of the system's dynamics[327]. He further developed feeback control laws based on this formulation for body reorientation[328]. Chen builds upon Sreenath's work on spatial open-chain multi-body systems with zero momentum and develops a non-smooth control feedback law based on the multi-cycle joint motion path-planning method[62]. Koon in his PhD thesis performs Lagrangian reduction to propose optimal control laws and compares this method of reduction to its symplectic (Hamiltonian) counterpart[171]. Shen, Schneider and Bloch introduced a nonlinear path-planning and control approach in the shape-space of a multi-body system through reducing its dynamics at zero angular momentum[313]. They plan system trajectories via shape change, analyze their controllability[152, 312], and further develop the controller for its implementation in a non-holonomic system[315]. Dynamical reduction of the phase space allows robots to produce aggressive and rapid movements by taking advantage of the symmetry to produce precise feasible motions[321]. Quadrotor UAVs, divers and other types of robots also benefit from having the ability to perform aggressive maneuvers[377]. Huang presents a nonlinear control algorithm that takes advantage of geometric properties of SO(3) as the configuration manifold of a UAV to design a controller capable of performing aggressive maneuvers, rejecting disturbances, rapidly correcting errors and precisely positioning[123]. Cortes et al. studied control of underactuated mechanical systems with symmetries and non-holonomic constraints from the viewpoint of affine connection control systems[73].

A benefit of dynamical reduction via symmetries is to lower the computational burden which allows equipment with lower computing capabilities to control a system. Avizzano developed a control methodology for Clavel's delta parallel robot using a series of geometric reductions that would decrease the computational load of an otherwise mathematically complex problem[37]. Model-predictive and RL-based controllers can also benefit from a lower computational burden as a result of the reduction process. Attitude of a rigid body, modelled on the Lie group SO(3), can be controlled with high computational efficiency via a model-predictive control, avoiding euler angle singularities, optimizing energy consumption and rejecting disturbances [382].

Apart from reduction by symmetry, other common reduction methods include truncation, reduced basis method, proper orthogonal decomposition, etc. Although these methods limit the model's accuracy, they allow researchers to propose GNC methodologies in smaller spaces.

7.2.2. Geometric Path Planning

Whether it is a complex spacecraft-manipulator system, a wheeled mobile robot or any other form of a dynamic system with symmetry and non-holonomic constraints, path-planners can benefit from improved performance or new control capabilities provided by geometric mechanics. Hussein and Bloch use theory of affine connections along with method of navigation functions and Lagrange multipliers to plan sub-optimal trajectories for a class of underactuated systems with non-holonomic constraints to avoid obstacles[141]. They also study constrained optimal trajectory following of a group of rigid bodies with configuration manifolds SE(3) in a finite time[140]. Shammas et al. analyze and generate gaits for mixed mechanical systems whose motion is simultaneously governed by a set of non-holonomic constraints and a conserved generalized momentum. Through proper recourse to geometric mechanics, they are able to show that the resulting motion has two portions: a geometric and a dynamic contribution[309, 308]. Recently, smart and efficient autonomous navigation techniques based on Riemannian motion policy have been introduced to use in deep learning for vehicle control purposes[213] and demonstrated competent performance in indoor motion control and obstacle avoidance.

7.2.3. Geometric Control

Geometric tools can be utilized in closed-loop control[145] to improve efficiency, elevate the control logic's capabilities to deal with underactuated systems[225], help unify holonomic and non-holonomic constraints[45], and introduce novel control algorithms for complex systems such as space manipulators[23]. Many robotic systems are underactuated and control inputs are usually applied through the robot's internal degrees of freedom. Even though these systems are relatively complex to control, geometric techniques can be proposed to guarantee their controllability on certain manifolds[314]. A free-floating space robot that is not actively controlled by an AOCS system is an underactuated system. Chen and Mukherjee showed that if unactuated joints in the manipulator have brakes, the overall system can be brought to full stop while converging to a desired terminal point, for a zero-momentum system[225]. Also, if the number of actuated degrees of freedom exceeds the unactuated ones and strong coupling exists between the two sets of states, the system can be stabilized at any desired configuration without actuation of the spacecraft. An integrated GNC logic is proposed by Viswanathan for several underactuated dynamical systems[377] that are modelled on SE(3), in the form of Lie group variational integrators using the discrete Lagrange-d'Alembert equation. An underactuated UAV was considered as a real-world application of this approach. Underactuated unmanned robotic systems such as wheeled vehicles can achieve self-balancing ability using geometric control techniques for controlled Lagrangian systems[342], via taking advantage of the Lie group exponential coordinates and using a logarithmic feedback in the reduced phase space. Flexible systems are also inherently underactuated and can benifit from geometric control laws. Control problem of an underactuated 3-DoF flapping plate with 2 actuators is studied by Taha[336], incorporating geometric control and averaging theory to stabilize the system.

7.2.4. Non-Holonomic Mechanics and Control

Non-holonomic constraints result from the conservation of momentum in the dynamical equation of a free-floating manipulator. Boltzmann-Hamel equations is a sample means to derive a model for such a system on Lie groups[210]. It describes the dynamics of the system in quasi-coordinates and is therefore able to include all holonomic and non-holonomic joints[209]. Duindam and Stramigioli derive these equations for non-holonomic multi-body systems on their global configuration manifolds, not its local coordinates[89]. Thus, they are able to avoid unreal singularities due to coordinate assignments in control design, and generate equations for multi-body systems with general holonomic or non-holonomic joints. Hussein and Bloch demonstrated advantages of utilizing affine connection formulation in optimal control of non-holonomic systems [141]. They minimize the control input of an underactuated, nonholonomic wheeled robot. They do not incorporate the symmetry properties of the system in their formulation. Olfati-Saber in his PhD work explores reduction of underactuated holonomic and nonholonomic Lagrangian mechanical systems with symmetry [252] and develops nonlinear control methodologies for them. He uses feedback linearization in reduced phase space to develop control laws[253]. Though, he only considers abelian symmetry groups and does not investigate systems with nonzero momentum. Grizzle builds upon Olfati-Saber's work by showing that planar robots that have one cyclic unactuated state can always be locally controlled[110]. Chhabra and Emami developed a two-stage dynamical reduction procedure for non-holonomic multi-body systems with the focus on a class of distributions that is invariant under the action of the symmetry group[66]. They considered multi-DoF joints and used chaplygin and symplectic reduction theorems, in this procedure. In a separate work, they also proposed a reduction method for multi-body systems with holonomic joints and constant momentum[67]. The conservation of nonzero momentum is resulted from the symmetry group action of the relative configuration manifold of the first joint, and symplectic reduction can be used to express the behaviour of the system in a reduced manifold. This research led to the first unified output-tracking control structure for underactuated, constrained robots with symmetry based on feedback linearization in the reduced phase space[68]. This control was implemented in space manipulators and rover systems. Muralidharan implements a geometry-based nonlinear control to a spherical robot[228] to achieve strong accessibility and small-time local controllability. He demonstrates asymptotic stability of the position and reduced-attitude controllers with an almost global domain-of-attraction. Khadem et. al carried out a geometric reduction procedure on a non-holonomic needle-steering controller resulted in the design of a 2-step control scheme to move the needle on a stable manifold corresponding to inserting and retracting the needle[162]. Martinez and Cortes demonstrate that by Lagrangian reduction of robotic systems locomotion concepts naturally appear in the optimal control problem[208, 141].

7.2.5. Advanced Geometry-based Control

Both the motion of the base spacecraft and the arm can be concurrently controlled using only the actuation of the joints, as demonstrated by Nakamura and Mukherjee[234]. Tortopidis and Papadopoulos developed a concurrent analytical path planning logic for an underactuated free-floating spacecraft-manipulator with nonholonomic constraints[348]. Controlled Lagrangian Method (CLM), also known as the energy shaping method, is often used to stabilize Lagrangian systems by shaping the input energy and external forcing functions[342]. Tashakory incorporates CLM to control a brachiation robot[341]. Wee et al.[383] demonstrate an adaptive motion control logic by using a parameter estimation law to find the unknown parameters of the system exploiting its geometric physical properties emphasising on the use of momentum integrals. Gentle grasp methods are recently gaining attraction in various areas of space robotics to handle samples (planetary rovers), satellites/debris (OOS) or even entire rocky objects (asteroid mining)[126]. Caging-grasp is a recently developed concept for OOS missions that uses a snake-like underactuated soft arm to gently encircle and capture a target object[122, 163]. Controllers based on Conformal Geometric Algebra (CGA) are prevalently used in underactuated snake-mimicking robots that are of particular importance to caging-grasp. Hrdina employs Clifford algebra (special application of CGA) to solve local controllability problem of an underactuated n-link snake robot[127]. He develops control schemes for a trident snake robot and demonstrates that CGA eases model modification[128]. He also solved trident snake robot's local controllability problem via differential geometric tools. In addition, Navart and Matousek[238] demonstrated capability of CGA (specifically a 5-D CGA) in controlling a simulated 3-link robot. A guided motion planning for snake-shaped robots in both forward and backward directions is developed by Guo et al.[113]. They combine Hamilton-Jacobi-Bellman equation in an optimal controller with dynamical reduction of its motion to be able to control an underactuated snake. Another grasping idea is to use a series of hollow end-effectors to cage two opposite ends of non-graspable objects[420].

8. Robustness in Dealing with Environmental disturbances

The GNC system responsible for planning and controlling the arm and the base motion must be able to compensate for the uncertainties in the system and external disturbances. Examples of the former are measurement and actuator model uncertainties[401, 130], and the slow drift in the (assumed conserved) total momentum of the system[322]. The latter includes effects such as Solar Radiation Pressure (SRP), aerodynamic drag, high order gravitational effects and other orbital disturbances. SRP is one of the most thoroughly studied orbital disturbance in the literature regarding spacecraft control and design[99]. Neglecting effects of any of these disturbances will cause the controlled spacecraft-manipulator system to deviate from its expected behaviour[91]. The coupling effect of the arm on base has also at times been treated as a disturbance source in controller design[86]. Induced by potential fields, the gravitational and magnetic disturbances show up in the $\begin{bmatrix} N_b & N_m \end{bmatrix}^{\mathbf{tr}}$ matrix in the equations of motion (Equation 17), and SRP (τ_{SRP}) and drag (τ_d) effects are entered as input forces on the right hand side of the equation.

8.1. Sources of Disturbance in Orbit

Solar radiation pressure is a relatively well-known force mostly effective in the GEO and higher altitude orbits, and is caused by the impact of photons coming from the Sun to the body and panels of a spacecraft. It depends on the cross section of the body exposed to the Sun, and hence, it is not a uniform force. Therefore, it causes changes in both orbital position and more importantly attitude of a spacecraft[102]. The effects of SRP is captured through the following equation[425]:

$$\tau_{SRP} = -\frac{SE\cos\theta}{c_{EM}} \begin{bmatrix} (1+\mu\nu)\cos\theta + \frac{2}{3}\nu(1-\mu) \\ -(1-\mu\nu)\sin\theta \end{bmatrix}_{\hat{n}\hat{v}}, \quad (64)$$

where S is the area of the exposed surface to SRP, E is solar irradiance, θ is the angle of incidence of radiation, c_{EM} is speed of light in vacuum, $\mu\nu$ is the proportion of incident radiation that is reflected specularly and the force is represented in the normal direction $\hat{n}$ and tangent $\hat{v}$ to the surface S. Though SRP has little effect in short term, in longer lasting operations it can cause noticeable perturbations in controller behaviour[146]. Orbital disturbances might include high order nonlinear gravitational effects due to earths oblateness or its non-homogeneous distribution of mass[174]. A method of formulating higher order gravitational disturbances is via spherical harmonics[274, 292] which gives the gravitational potential as

$$U_g(r,\theta,\phi) = \frac{\mu_E}{r_E}\sum_{n=1}^{\infty}(\frac{r_E}{r})^{n+1}\sum_{m=0}^{n}[C^s_{nm}\cos(m\phi) + S^s_{nm}\sin(m\phi)]P^m_n(\cos\theta), \quad (65)$$

where μ_E is the Earth's gravitational constant, r is the distance from Earth's center, r_E is Earth's reference radius, θ is the geocentric co-latitude, ϕ is the longitude, C^s_{nm} and S^s_{nm} are the fully normalized, unit-less spherical harmonic coefficients of degree n and order m, and P^m_n is the fully normalized associated Legendre function of degree n and order m.

One of the most dominant disturbances on any robotic system in the orbital environment, specially in LEO, is gravity gradient torque (τ_{gg}) that takes the following form in the body coordinate frame attached to the CoM of the system:

$$^b\tau_{gg} = 3(\frac{\mu_E}{r^3})(^b\hat{z}_o)^{\times}[(I_{loc})(^b\hat{z}_o)], \quad (66)$$

where $^b\hat{z}_o$ is the vectorial representation of the z axis of the orbital frame in the body coordinate frame, and I_{loc} is the locked inertia matrix of the spacecraft-manipulator system about its CoM. Contact force upon impacting the target, specially in the case of a non-cooperative target[248] and asteroid redirection[310], is another major source of disturbance that can be estimated as in[1] and must be remediated by the controller.

Magnetic interferences of the harsh outer space environment (specially magnetic storms[280]) is yet other source of unwanted external force that inputs any system in orbit, whether a single satellite or a space manipulator system[179]. Magnetic potential, similar to gravitational disturbance, has been formulated using spherical harmonics[179]. In low Earth orbits drag disturbances may also be considerable, whose growing effects can lead to drastic changes in the state of a spacecraft-manipulator system.

When neglecting disturbances, CoM of a spacecraft-manipulator system is considered fixed or moving at a constant velocity in the orbital frame, which is an inaccurate model of the real system in orbit. These effects are often overlooked, since ADCS system is typically assumed active. However, disturbance effects should be considered in the GNC system of a fully autonomous robotic system that operates in free-floating mode with the demand to concurrently control the base/manipulator motion and in the proximity of a sensitive target. Few research on spacecraft-manipulator systems consider the effect of disturbances[295, 116] and uncertainties in their dynamic formulation GNC design. They commonly include disturbances to show the robustness and effectiveness of adaptive control methods in comparison with simple linear time invariant feedback systems[33].

8.2. Control Methodologies to Reject Disturbances

Orbital disturbances, such as, SRP, gravity gradient, aerodynamic drag and magnetic forces, are minimal and often neglected[91]. A plethora of currently available control methodologies deal with robotic manipulators rejecting disturbances during operation through straightforward feedback control schemes[168] or optimal controllers specifically designed to reject disturbances[22]. The optimal control method (extended GJM) used by Rybus, Seweryn and Sasiadek has the capability of accounting for external forces[295]. Nonlinear controllers have the potential to actively reject external undesired effects on the trajectory-tracking performance of space manipulators[123]. CMAC algorithms, as seen in section 7.1 can facilitate robust control of spacecraft with uncertain dynamics[351]. Controllers based on SMC, due to their changing structure in response to unexpected disturbances and modelling flaws, are promising to provide a robust control performance for free-floaters, in orbit[385]. Robust controllers such as H_2, H_∞ and $\mu - synthesis$ are some of the most efficient nonlinear controllers for tip position tracking of flexible spacecraft[202, 201]. Robustness is even important in identification phase, considering harsh lighting conditions in outer space. Aghili and Parsa used vision systems to robustly estimate the state of their orbital target[18, 16]. Although they included some aspects of orbital mechanics for more accurate estimates, they did not include any effect of environmental disturbances on the dynamics of the target.

9. Conclusion

Orbital missions, including on-orbit servicing, satellite/station assembly, probing extra-terrestrial objects and space debris mitigation, are frequently conducted as part of space exploration and exploitation programs. Performed in remote and hostile outer space environments, these missions greatly benefit from space manipulators that can offer universal and autonomous technological solutions. The focus of the current paper, consisting of two parts, was on the role of guidance, navigation and control systems of space manipulators deployed in orbital missions.

In the first part, common phases of in-orbit robotic missions were identified and various classes of developed GNC methodologies for each phase were extensively reviewed. A formulation for the kinematics and dynamics of spacecraft-manipulator systems was presented to unify the notation for the reported GNC methodologies. This furnished a comparative discussion on different families of GNC solutions that were summarized in multiple tables, at the beginning of each section. In the current survey, the emphasis was placed on the study of GNC methodologies utilized in attitude synchronization, manipulator deployment, and capture phases, specially the ones reported for use in the two free-floating and free-flying operating regimes of space manipulators. Free-floating systems require compensation of the disturbing reaction induces on the base spacecraft, due to the arm motion. Many GNC techniques evaluating and addressing such disturbances, such as GJM, RNS, Disturbance Map, and optimal control, were discussed in details. Free-flying systems use a separate control channel to keep the base spacecraft stationary, and thus, their arm's GNC can only focus on the control of end-effector motion. However, the base control can result in considerable fuel consumption and may push the system to unstable regions. GNC techniques for free-fliers, most of which are similar in nature to those for freely floating systems, were also studied. The partially-known nature of the outer space environments and orbital targets demands adaptable and robust GNC methodologies. Various adaptive, robust, varying-structure and other uncertainty/disturbance rejecting GNC techniques were extensively reviewed. Flexibility of the arm, joints or the target has a non-negligible effect on the behaviour of the GNC system, which has been widely researched in the literature. This effect is separately discussed in some sections of this paper. Capturing the target requires a considerable amount of meticulous planning in advance. GNC methodologies were reported that planned pre-grasp trajectories either to minimize impact forces or maximize the end-effector compliance to absorb the shock. Similarly, post-grasp GNC techniques have been designed to damp the unknown, unwanted tumbling motion of the target.

In the second part of this paper, the authors' vision for future developments of GNC systems for autonomous in-orbit robotic missions was detailed, delving into the applications of AI and geometric mechanics. Different readily available methods that may or may not have been applied to space robotics were listed and their potential applications to the GNC of space manipulators were discussed. The capabilities of each method in overcoming obstacles in GNC of in-orbit robotic missions were reported and their advantages, whether being simplifying, strengthening or numerically enhancing a GNC procedure, were illustrated. An exclusive discussion on the orbital disturbances and their threats to the long-term autonomy of space robotic systems concluded the paper.

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