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# A review of space robotics technologies for on-orbit servicing

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ABSTRACT

Space robotics is considered one of the most promising approaches for on-orbit servicing (OOS) missions such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbital debris removal. Many enabling techniques have been developed in the past two decades and several technology demonstration missions have been completed. A number of manned on-orbit servicing missions were successfully accomplished but unmanned, fully autonomous, servicing missions have not been done yet. Furthermore, all previous unmanned technology demonstration missions were designed to service cooperative targets only. Robotic servicing of a non-cooperative satellite is still an open research area facing many technical challenges. One of the greatest challenges is to ensure the servicing spacecraft safely and reliably docks with the target spacecraft or capture the target to stabilize it for subsequent servicing. This is especially important if the target has an unknown motion and kinematics/dynamics properties. Obviously, further research and development of the enabling technologies are needed. To motivate and facilitate such research and development, this paper provides a literature review of the recently developed technologies related to the kinematics, dynamics, control and verification of space robotic systems for manned and unmanned on-orbit servicing missions.



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## 1. Introduction

Statistical data reveal that, on average, 100 satellites (from 78 to 130) were launched every year in the past decade. Most of them performed their missions without any major problems. However, a small number of them experienced anomalies and even failures of various degrees of severity [1]. In the past, launcher failure was the most common cause of failure. However, on-orbit failures have exceeded launch failures in recent years for the first time [2] and cumulatively account for losses of billions of dollars [3]. Besides, every launched satellite eventually runs out of fuel and thus, must be decommissioned even if the satellite may still be functional [4]. A number of studies [5–7] have demonstrated potential savings in terms of cost effectiveness of in-flight repair of damaged spacecraft, and a model that also includes risk and uncertainties analysis was presented by Sale et al. [8,9]. For these reasons, the National Aeronautics and Space Administration (NASA) realized the importance of robotics on-orbit servicing operations to protect their assets in space as early as the 1980s [10,11]. The term *on-orbit servicing* (OOS) refers to the maintenance of space systems in orbit, including repair, assembly, refueling and/or upgrade of spacecraft, after their deployment. It is notable that such complex space missions have motivated the development of new space robotics technologies and several experimental demonstration missions including both manned and unmanned missions [12].

A space robotic system (also referred to as space manipulator or space robot) for an OOS mission typically consists of three major components: the base spacecraft or servicing satellite, an *n*-degree-of-freedom (*n*-DOF) robot manipulator attached to the servicing satellite, and the target spacecraft to be serviced. A spacecraft-manipulator servicing vehicle (illustrated in Fig. 1) is sometimes termed the servicing system.

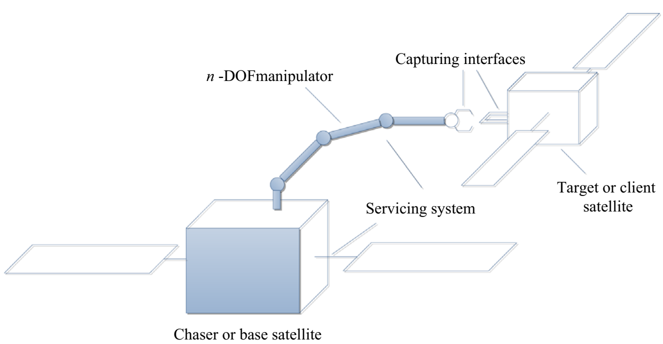


**Fig. 1.** Components of a spacecraft servicing system for on-orbit servicing.

The capturing process includes a series of operations. After having completed the far and close-range rendezvous maneuvers [13] with the target satellite, the servicing spacecraft remains at a safe, station-keeping, distance from the tumbling target satellite. Then, the capture operation mode starts, which may be divided into four phases. The first phase corresponds to the observing and planning phase for acquiring motion and physical properties information about the target satellite, to plan how the robot manipulator should grasp the target. The second phase is to control the robot to move toward the planned grasping location, such that the robotic arm is ready to capture the target. The third phase consists in the actual capture (physical interception) phase in which the manipulator physically grasps the capturing device of the target satellite. The fourth phase is the post-capture phase, where the captured target is stabilized along with the servicing system. Fig. 2 shows the four phases of the capturing maneuver.

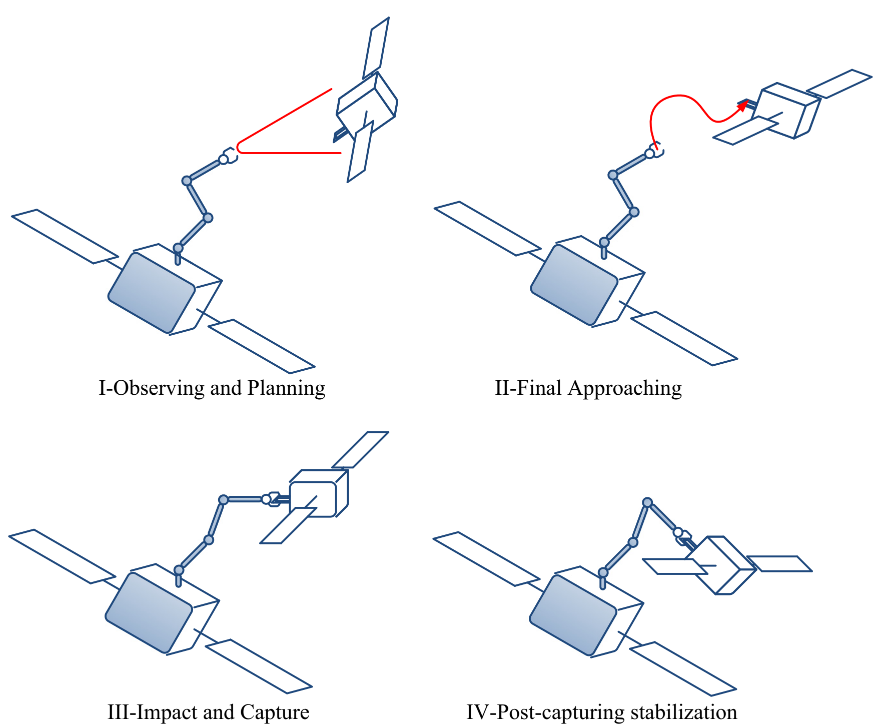


**Fig. 2.** The four phases of a satellite capturing operation.