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Obstacle avoidance in space robotics: Review of major challenges and proposed solutions

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ABSTRACT

Manipulators can be utilized for various purposes during space missions, e.g., Canadarm2 manipulator mounted on the International Space Station assists in station construction and maintenance. Up to now, with only a few exceptions, manipulators in space were always controlled by astronauts or by operators on the ground. However, new ambitious missions, such as on-orbit servicing missions and active debris removal missions, will require a high level of autonomy and will pose new challenges in the field of space robotics. One of such challenges, addressed in this paper, is the problem of obstacle avoidance. This problem has been divided into three topics: (i) collision-free trajectory planning of a space manipulator mounted on a large orbital structure (such as a space station), (ii) collision-free trajectory planning of a manipulator mounted on a relatively small satellite, and (iii) collision-free trajectory planning of a space robot moving in proximity to a large orbital structure. For each topic, major challenges are identified and proposed solutions are reviewed. The presented review shows that the collision-free trajectory planning in space robotics is a very active field of studies, but there are still several open problems that need to be solved before the proposed methods could be applied during on-orbit servicing, active debris removal and on-orbit assembly of large structures.

1. Introduction

Space robotics is an active and quickly growing technological field. Manipulators can be utilized for various purposes during space missions. The Shuttle Remote Manipulator System (SRMS) was used on the Space Shuttle to deploy satellites, to capture them, and to assist astronauts during Extra Vehicular Activities (EVA) [1]. The Space Station Remote Manipulator System (SSRMS) mounted on the International Space Station (ISS) is used to capture unmanned resupply ships (such as Dragon and Cygnus) and also to assist in station construction and maintenance [2,3].

Apart from a few experiments (e.g., [4]), up to now, manipulators in space were always controlled by astronauts or by operators on the ground. However, new ambitious space missions that are currently planned will require a high level of autonomy and will pose new challenges in the field of space robotics. The proposed unmanned on-orbit servicing (OOS) missions aim at prolonging operational lifetimes of Earth-orbiting satellites by conducting on-orbit repairs and refueling [5]. Studies show that on-orbit servicing would be economically feasible (e.g., [6,7]). Therefore, several proposals for such missions were presented (e.g., [8–10]). The same technologies that are required for OOS missions could also be utilized in the active debris removal (ADR) missions. The aim of the proposed ADR missions is to capture and remove from orbit large space debris that threatens other satellites [11]. Studies show that ADR missions are required to stop the growth of Low Earth Orbit (LEO) debris population resulting from the spontaneous collisions of orbiting objects [12]. From various possible methods to perform on-orbit capture maneuver the use of a manipulator is usually proposed in missions that are currently considered [13]. In case of OOS and ADR missions, the manipulator will be mounted on a relatively small satellite. Thus, the motion of the manipulator will influence position and orientation of this satellite [14].

It is envisaged that in near future space robots, i.e., small and highly autonomous satellites equipped with manipulators, will also be used for on-orbit assembly of large structures, such as large space telescopes (e.g., [15]), space-based solar power satellites that would collect solar power on-orbit and send it to Earth (e.g., [16]), or even large solar sails (e.g., [17]). On-orbit assembly of large vehicles for human exploration of Mars is also considered [18]. Using space robots instead of astronauts for assembly work will minimize risk for humans and will significantly reduce mission costs [19]. Therefore, various concepts are proposed for using space robots for assembly of space telescopes (e.g., [20,21]) and

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space-based solar power satellites (e.g., [22]). To perform such assembly work space robots will have to perform several tasks such as grasping modules, connecting them, welding, fastening or twisting. Moreover, space robots will have to navigate in a clustered environment of the structure that will be assembled.

All missions described above pose new challenges and require advancements in the field of space robotics. One common problem that must be addressed in all these missions is the problem of obstacle avoidance. Methods for control and trajectory planning that take into account obstacles in the workspace were proposed for mobile robots and manipulators working on Earth since 1970' [23]. However, in the field of space robotics problem of obstacle avoidance is relatively new and was not extensively studied. Moreover, orbital environment poses several unique challenges for the obstacle avoidance.

This paper serves two main purposes. First, it aims at characterizing the obstacle avoidance problem specific for the orbital missions and reviewing major challenges. Secondly, this paper provides a comprehensive review of proposed solutions for the obstacle avoidance problem in space robotics. Review papers dedicated to the problem of obstacle avoidance in Earth-based applications (such as [24] and [25]) do not cite papers devoted to the problem of obstacle avoidance in space. Review papers containing sections devoted to trajectory planning and control of space robots ([26–28]) seem to omit the problem of obstacle avoidance. Moreover, several important papers devoted to this problem were published in the last few years and, therefore, are not included in any literature reviews. Thus, to the best knowledge of the author, this is the first review devoted to the obstacle avoidance problem in space robotics.

For the purpose of this study the problem of obstacle avoidance in space robotics has been divided into three topics: (i) collision-free trajectory planning of a space manipulator mounted on a large orbital structure (such as a space station), (ii) collision-free trajectory planning of a manipulator mounted on a relatively small satellite that could be used in OOS and ADR missions, and (iii) collision-free trajectory planning of a space robot moving in close proximity to a large orbital structure (e.g., for the purpose of performing assembly work). The paper is organized as follows. Major challenges in obstacle avoidance are presented in Section 2, while proposed solutions are reviewed in Section 3. Each of these two sections is divided into three subsections devoted to the specific topics defined above. The discussion is presented in Section 4 along with possible directions for future research. The paper ends with short conclusions in Section 5.

2. Major challenges in obstacle avoidance

2.1. Manipulators mounted on large orbital structures

Manipulators that are currently operated in space are mounted on the ISS, which is a large orbital structure. The station's primary remote manipulator system is called the Mobile Servicing System (MSS). This system is composed of three components: (i) Mobile Base System (MBS) which rides on rails attached to the ISS's main truss, (ii) SSRMS manipulator known as the Canadarm2, and (iii) Dextre two-arm robotic manipulator. Canadarm2 is a 17.6 -m long 7 DoF manipulator developed by MDA Space Missions for the Canadian Space Agency's contribution to the ISS [29]. It is used in the ISS assembly and maintenance, it assists astronauts during EVA, transports equipment around the station and is used to catch resupply vehicles (such as Dragon). The Canadarm2 was also used for experiments related to OOS (Robotic Refueling Mission [30]). Another manipulator that is currently operated on ISS is the 10-m long Remote Manipulator System (JEM-RMS) mounted on the Japanese Experiment Module (JEM) [31]. New manipulator, called the European Robotic Arm (ERA), will be delivered to ISS in 2018 [32]. Comparison of robotic systems operating on ISS can be found in Ref. [33], major challenges in operations of such manipulators are presented in Ref. [34], while their basic parameters are summarized in Table 1. It is envisaged that manipulators will play an important role in operations of future large orbital structures, e.g., a 10-m long manipulator is proposed for the Chinese Tiangong space station [35]. Large manipulators might also be used during operations of the Deep Space Gateway – a space station in the lunar orbit proposed recently by the National Aeronautics and Space Administration (NASA) [36]. Visualization of a manipulator mounted on a large orbital structure is presented in Fig. 1.

Table 1
Parameters of manipulators used on the ISS.

Manipulator	Year of delivery	Total length [m]	Mass [kg]	Ratio of manipulator mass to ISS mass [%]
Canadarm2	2001	17.6	1800	0.43
JEM-RMS	2008	10	780	0.19
ERA	2018 (planned)	11.3	630	0.15

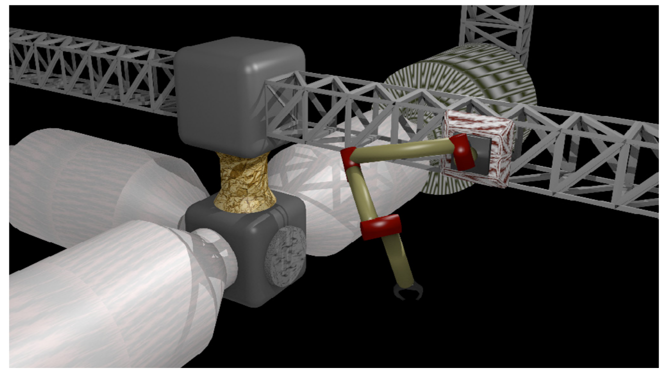

Fig. 1. Visualization of a manipulator mounted on a large orbital structure.

Another example of a manipulator mounted on a relatively large structure was the Shuttle Remote Manipulator System (SRMS), also known as the Canadarm [37]. It was a 15.2-m long manipulator that was used on the Space Shuttle to deploy, capture and repair satellites, position astronauts, maintain equipment, move cargo and assist construction of the space station. Total mas of the Canadarm was 410 kg, while the mass of the Space Shuttle was about 70 000 kg. Thus, influence of its motion on the position and orientation of the Space Shuttle could in some cases be neglected. The Canadarm, operated by astronauts, worked in the proximity to complicated structures (the ISS, the Space Shuttle itself, payloads in the shuttle cargo bay, such as the Hubble Space Telescope) and avoidance of collisions was an important issue.

As shown in papers presented in Section 3.1, manipulators mounted on large orbital structures can be treated as fixed-base manipulators due to the fact that the mass of such structure and its inertia are high in comparison to mass and inertia of these manipulators (e.g., mass of the ISS in its current configuration is around 420 000 kg, while mass of the Canadarm2 is only 1800 kg). Even when a heavy payload is transported by a manipulator, the influence of the manipulator motion on the state of the orbital structure can in some cases be neglected. However, it must be noted that a simple comparison of the manipulator and payload mass to the mass of the structure is insufficient to assess the influence of the manipulator motion on the state of the structure. This influence also depends on the mass moment of inertia, the manipulator length, and selected trajectory. When only the possible collisions of the manipulator with the structure itself are considered, the motion of the structure induced by the motion of the manipulator does not influence the relative positions of obstacles in the manipulator workspace. In such cases and in cases where this influence can simply be neglected the trajectory planning methods used for fixed-base manipulators working on Earth could be directly applied for autonomous operations of space