On the Possible Utilization of an End-Effector Mechanism for Space Debris Remediation in Low Earth Orbit

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Abstract. Research and development in the field of Space Debris Remediation (SDR) technologies has gathered rapid momentum in the last two decades. Amongst a variety of technologies which are being investigated, the robotic manipulator coupled with an end-effector system offers a feasible option for active SDR missions. In the current work, the utilization aspect of a robotic system is addressed by conducting a focused survey of pertinent utility characteristics associated with the practical employment of the system. One such configuration that merits special attention is the possible employment of a 4-degrees of freedom robotic system integrated with an end-effector mechanism which uses a Light Detection and Ranging (LIDAR) system for the identification of debris. Additional investigation into universal mathematical models related to key utilization aspects can also be conducted for use in the future phases of this continual project. This paper is formulated to act as a bridge between space robot design and its application domains.

Keywords: Space Debris Remediation (SDR), End-effector, Robotic arm.

1 INTRODUCTION

The term space debris refers to all types of natural or man-made or “anthropogenic” objects which are orbiting as close as LEOs to as far as GEO. Generally, anthropogenic debris consists of defunct spacecraft, rocket bodies, fragmentation debris, and mission-related debris [1]. Although, space debris moving in the earth’s orbits at velocities over 7 km/s, has been realized as major a safety concern since the early 1970s, however, research and development in the field of Space Debris Remediation (SDR) technologies has gathered rapid momentum in the last two decades. This sudden spike of interest may be attributed towards the concept of “Kessler Syndrome”, which predicts that with a linear increase in the number of satellites, the quantity of debris grows exponentially.

The debris growth model presented by Kessler et al. [2] is a seminal foundation of all later research in this field. Interestingly, the approximated debris growth in the last 60 years is observed to be exponential which closely resembles Kessler's predictions made in his later work in 1989 [3]. This practical manifestation of Kesler's Syndrome can be easily visualized in **Fig. 1** which depicts a year-on-year change in the number of catalogued debris objects in Earth's orbit. As an extension to this plot, **Fig. 2** shows the projected environment of LEO in the next 200 years. This projection is based on NASA's orbital debris population model called LEGEND.

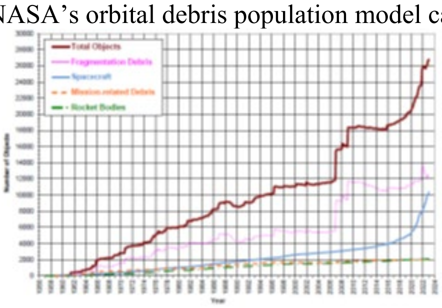

Fig. 1. Number of catalogued debris objects as of 03 Feb, 2023. Ref [4]

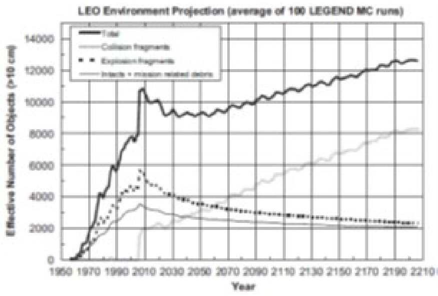

Fig. 2. Projection of debris environment in LEO for next 200 years using LEGEND probabilistic model. Ref [5]

A summary of statistical data pertaining to trackable (> 10 cm), un-trackable (< 10 cm), and micro-sized(< 1 cm) debris, retrieved from ESA's discosweb portal is summarized in **Table 1**, whereas, data pertaining to catalogued debris objects in various orbits in presented in **Table 2**.

Even though the above discussion on debris population is far from exhaustive, it is readily evident that the growth of space debris is not only a prevalent issue, but an exponentially growing phenomenon. Thus, necessitating focused research on the design and development of its remediation technologies. Contemporary technologies being investigated for SDR are divided in two broader categories; "contact-based" and "non-contact-based" remediation technologies. For non-contact-based remediation, a wide variety of technologies have been investigated [7] which include 'Electrostatic Tractor'.[8], 'Gravity Tractor' [9], laser-based systems [10], and Ion-beam Shepard-based

Table 1. Estimates of debris population (with respect to size) based on Master-8 model (updated Mar, 2023) Ref [6].

1mm~1cm	1cm~10cm	> 10cm
130 mil	1 mil	36,500

Table 2. Number and mass of catalogued (>10 cm) debris objects (updated Mar, 2023). Ref [6]

Orbit	Count	Mass (tons)
LEO	20537	4310.9
MEO	543	111.1
GEO	907	2721.9
GTO	1246	658.3
Other	10153	3065.4
Total	33486	10867.7

systems [11] etc. However, as these technologies are beyond the scope of this paper, therefore they will not be discussed in detail.

The contact-based capturing technologies include; robotic arms [12], tethered-net / gripper capturing [13], tethered-net robots [14], and harpoon mechanisms [15] etc.. A diagrammatic representation of some of the prominent contact-based remediation technologies is presented in **Fig. 3**.

Fig. 3. Concept diagrams of contemporary SDR systems.

2 End-effector integrated robotic systems

Robotic systems with manipulator arms and gripping end effectors are regarded as highly effective contact-based technology for SDR missions [16]. Compared to other SDR methods; robotic systems are reusable entities, backed by over 30 years of experiential data. A list of robotic systems which have a successful track record in space applications, is presented in **Table 3**.

Considering above discussed advantages, a 4-DoF robotic system (code named: Precision Autonomous Capturing and Maneuvering system or "PACMAN") was designed and a concept demonstrator was developed for SDR missions in LEOs [17]. Inverse kinematics were modelled using Denavit-Hartenberg (D-H) method and debris position vector was attained using Light Detection and Ranging (LIDAR) mechanism. **Fig. 4** shows a view of PACMAN installed on a pseudo-satellite bus.

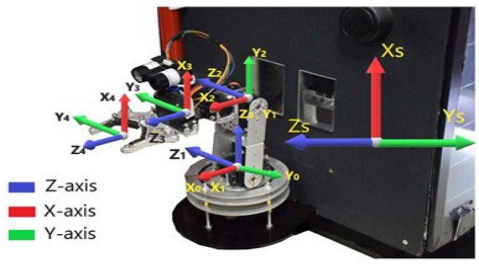

Fig. 4. Precision Autonomous Capturing and Maneuvering system "PACMAN". Ref: [17]

In the first phase of the research, following core queries have remained un-answered:

1. The dynamic behavior of chaser satellite and target (debris) has not been addressed and both are considered stationary in absolute vacuum.
2. The utility characteristics such as scalability and orbit application etc. have not been addressed

In this paper, a focused survey of various key utilization aspects associated with space robotic systems has been conducted for utilization in LEO SDR mission.

Table 3. Prominent robotic systems utilized in space applications.

Robotic System	Spacecraft/Satellite	Agency	Years in Service
Canadarm2	ISS	CSA, NASA	2001-present
ARA	ETS-7	JAXA	1997
Dextre	ISS	CSA, NASA	2008-present
Robonaut (R2)	ISS	NASA	2012-present
ERA	Shuttle-Mir	NASA	1995-1998
TAGSAM	OSIRIS-REx	NASA	2016 - present
LPRS	Chang'e 5	CNSA	2020 - present

3 Utilization

The utilization of end-effector mechanism can be discussed by surveying a variety of technical as well as non-technical criteria. However, for brevity of discussion, current survey is focused on following utility aspects:-

a. High-fidelity mathematical models
b. On-orbit handling
c. Scalability
d. Applicability to varying orbits

3.1 High Fidelity Mathematical Models

One of the prime utility characteristics of robotic systems, is availability of robust mathematical models for practical application in mission design. These models can be broadly segregated into following categories: -

Kinematic Models. These models deal with motion of robotic links and joints to achieve the desired end state. These models are used to solve complex kinematic problems and to achieve autonomous control of single or dual arm robotic manipulators [18, 19]. General form of this kinematic model can be expressed as follows:-

$$\dot{\Phi}_M = \left[J^*\right]^{-1}\left(\dot{X} - \dot{X}_0\right)$$

This model solves the joint rates of robotic manipulator (left-hand side) by utilizing known motion rate of end-effector (right hand side).

Dynamic Models. These models are used to investigate the mutual interaction of chaser and target in terms of internal and external forces. Robust dynamic models have been developed based on Newtonian and Lagrangian approaches [13]. One of such models which has been profoundly explored in literature has the following generalized form:-

$$M\ddot{\Phi} + C\dot{\Phi} = \sum F \pm \eta F_{Contact}$$

In this model, the inertial and Coriolis / centrifugal forces (left-hand side) are balanced by the external and contact forces (right-hand side). A variety of solutions are attempted by researchers, including design of precise grasping maneuvers [20], designing AOCS (Attitude and Orbital Control System) [21], and design of optimal capture trajectory [22] etc.

Contact Force Models. The contact force on end-effector is typically modelled by segregating it into normal and tangential components. The normal component is then modeled by utilizing Hertz Law [23], Linear Spring-Dashpot Model [24], or Non-Linear Spring-Dashpot Model [25]. Whereas, the tangential component is commonly modelled by using Coulomb's Friction Law [26]. Generic form of contact force model can be written as follows: -

$$F_{Normal} = K\delta^x + \lambda\delta^x\dot{\delta}^y$$
$$F_{Friction} = \mu_k F_{Normal}$$

K, C : Stiffness and Damping coefficients

δ : Virtual Deformation Depth

λ : Non-linear damping coefficient

μ_k: kinetic friction coefficient

3.2 On-orbit handling

The end-effector based robotic systems can be utilized in fully autonomous, semi-autonomous, and manual modes. With the availability of inverse Jacobian based kinematic models (discussed above) coupled with fast processing computational systems, semi and fully autonomous on-orbit handling of end-effectors is practically achievable for SDR operations, thus enabling the development of completely independent systems in near future [27].

Using the kinematic approach to address the 'on-orbit handling' of robotic systems, a number of robust schemes and algorithms have been developed and are readily available in open literature [12]. Some of the notable examples are; development of reactionless maneuvering algorithm [28], dual-arm coordinated capture of target [29], and analysis of the effect of end-effector movement on the base of robotic arm [30] etc.

3.3 Scalability

In general, an engineering system is considered efficiently scalable only on the premise that its performance either increases or at-least remains constant with the increasing system size [31]. However, for mutually coordinating systems, the communication delays and shared resource allocation may diminish the overall performance, thus necessitating an analytical investigation of scalability before the mission design phase. Scalability analysis is typically accomplished by using phenomenological models which provide a reasonable fit on experimental data. One of the seminal models to evaluate the scalability characteristic is Amdahl's law [32] which predicts the speedup 'S(n)' of overall system when utilizing ‘n’ number of parallel sub-systems. Generalized form of Amdahl’s law is as follow:-

$$S(n) = \frac{n}{1+\phi(n-1)} \; : \; 0 \le \phi \le 1 : \text{time fraction of each serial task}$$

Numerous re-evaluations of this scalability law are available in open literature; Gustafson’s Law [33] to attain optimistic estimates of speedup, and Gunther’s Universal Law [34] to scale a shared-resources based system; are a few prominent examples. Similarly, numerous scalability algorithms such as algorithm for ascertaining the limits of scalability [35], bifurcation of robotic tasks into solo & group actions [31], scalability of super linear models [36], and scalability of multi-core processing systems [37] etc. provide a solid foundation for realistic upscaling or downscaling of the designed robotic system, during the mission design phase.

3.4 Applicability to Varying Orbits

Applicability of SDR system to specific orbits depend upon the debris population or density which satisfies the operational limitations of considered system. In this regard, various statistical and probabilistic models are available in open literature which provide analytical solutions to estimate the number of debris objects in particular orbit and their respective probability of collision in future [1, 3, 38].

Based on the physical limitations of end-effector system to capture only a limited range of debris (medium to large sized), these models are required to be utilized in the ‘inverse’ manner i.e. robotic system SDR mission is typically designed to “avoid” the high flux areas of debris, particularly in the range of 1 cm to 10 cm diameter, to preclude any damage to the system itself. Consequently, for the initial orbit allocation, critical debris objects in low density orbits can be termed as “prime candidates”. A sample study [39] conducted for robotic SDR mission is displayed in Table 5. This data clearly depicts the orbits of interest during early phases of robotic system based SDR operations.

3.5 Conclusion

A focused mini-survey has been performed to determine the utilization aspects of an end-effector based robotic manipulator system (code named: PACMAN- Precision Autonomous Capturing and Maneuvering system). Key utility aspects (such as availability of high-fidelity mathematical models, scalability characteristics, applicability to varying orbits etc.) have been explored with an objective to utilize these aspects as mission design considerations and/or boundary conditions during future phases of research. The scope of work is presented in a tutorial format to act as a bridge between robotic system design for SDR operations and its practical application domains.

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