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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 various technologies 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-degree-of-freedom robotic system integrated with an end-effector mechanism that 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 mechanism, Robotic arm, Active SDR.

1 Introduction

The term space debris refers to all types of unwanted natural or man-made ("anthropogenic") objects which are orbiting Earth 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 have gathered rapid momentum in the last two decades. This sudden spike of interest may be attributed to 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 latest statistical and observational data on space debris shows a similar growth trend as predicted by Kessler's model. A summary of statistical data of trackable (> 10 cm), un-trackable (< 10 cm), and micro-sized (< 1 cm) debris, retrieved from ESA's opensource portal is summarized in **Table 1**, whereas, data of cataloged debris objects in various orbits in presented in **Table 2**.

Table 1. Estimates of debris population (concerning size) based on Master-8 model (updated Mar 2023) Ref [3].

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

Table 2. Number and mass of cataloged (>10 cm) debris objects (updated Mar 2023). Ref [3]

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

Different types of methodologies which are being actively researched for the resolution or remediation of space debris are known as Space Debris Remediation (SDR) technologies. Contemporary SDR technologies can be divided into two broader categories; "contact-based" and "non-contact-based" remediation technologies. Non-contact-based include 'Electrostatic Tractors'.[4], 'Gravity Tractor' [5], laser-based systems [6], and Ion-beam Shepard-based systems [7] etc. Whereas, contact-based capturing technologies include; robotic arms [8], tethered-net / gripper capturing [9], tethered-net robots [10], and harpoon mechanisms [11], etc. A diagrammatic representation of some of the prominent contact-based remediation technologies is shown in **Fig. 1**.

Fig. 1. 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 [12]. To investigate the practical utilization of these systems, 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 [13]. Inverse kinematics for this system was solved using the Denavit-Hartenberg (D-H) method in which the debris position vector was attained using the Light Detection and Ranging (LIDAR) mechanism. PACMAN is shown in **Fig. 2** below.

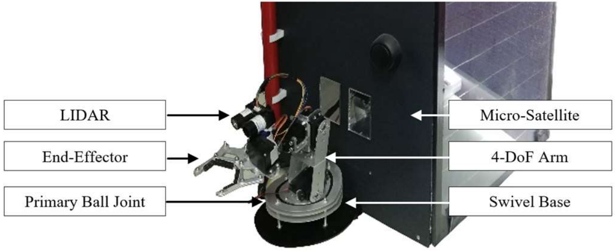

Fig. 2. 4-DoF SDR system (PACMAN) installed on a pseudo-satellite bus.

In the first phase of the research, the utility characteristics of end-effectors such as scalability and on-orbit application, etc. had not been addressed independently. Therefore, this paper conducted a focused survey of various key utilization aspects associated with end-effector-integrated space robotic systems for utilization in SDR missions in LEOs.

3 Utilization Aspects

The utilization aspects of the End-Effector mechanism can be discussed by surveying a variety of technical as well as non-technical criteria. However, for the brevity of discussion, the current survey has been focused only on key utility features, and the same are briefly discussed below: -

3.1 Utilization of Legacy Parts

One of the primary concerns related to technology development is the availability of reliable and tested parts. Since the last three decades, a wide variety of end-effectors have been actively utilized on board robotic systems for versatile space mission requirements [14]. Thus, time-tested robust legacy parts can be readily utilized for the rapid development of mission-specific end-effectors, considerably reducing the time and cost associated with the development of technology from scratch. Some prominent end-effector integrated robotic systems utilized in space applications are shown in **Table 3**.

Table 3. Prominent robotic systems are 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	Change 5	CNSA	2020 - present

3.2 Utilization of Universal Mathematical Models

Mathematical models are the backbone of any technological development and these are often required to be evaluated from scratch. However, for robotic systems in general and space robotics in particular, existing universal math models can be successfully utilized for novel system designs. Prominent models used for space robotic systems design are as follows: -

(a) **Inverse-Kinematic Models.** These models are used to evaluate the position and angles of robotic links and joints to achieve the desired position and angle of the End-Effector. These models are extensively used to design autonomous control of single or dual-arm robotic manipulators [15, 16]. The universal model can be written as: -

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

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

(b) **Dynamic Models.** These models are used to investigate the mutual interaction of robotic systems and target objects in terms of internal and external forces. The mathematical formulation based on Newtonian and Lagrangian approaches [9] can be written in 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). Examples of utilization include the design of precise grasping maneuvers [17], the designing of AOCS (Attitude and Orbital Control System) [18], and the design of optimal capture trajectory [19], etc.

(c) **Contact Force Models.** The contact force on the end-effector is typically modeled by segregating it into a normal component (modeled by Hertz Law [20], Linear Spring-Dashpot Model [21], or Non-Linear Spring-Dashpot Model [22]), and tangential/frictional component (modeled by Coulomb's Friction Law [23]). Universal form of contact force model can be written as follows: -

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

where,

K, C : Stiffness and Damping coefficients
δ : Virtual Deformation Depth
λ : Non-linear damping coefficient
μ_k: kinetic friction coefficient

3.3 Utilization in Multiple On-Orbit Tasks

A versatile utilization aspect of end-effectors is the ability to perform a wide variety of tasks in LEO. For example, the end-effector designed to grasp tumbling debris (non-cooperative objects) is equally qualified to grasp and manipulate active satellites' components (cooperative objects). Thus, in the latent time between SDR operations, the robotic system with the same end-effector can viably perform a variety of on-orbit tasks [24] including satellite servicing, inspection, repair, replacement, re-alignment, docking support etc.

3.4 Utilization in Autonomous Operations

With the rapid advances in high-speed computational systems, it is now possible to use precision control algorithms to safely utilize the end-effectors in fully autonomous and semi-autonomous modes. In this context, several robust control schemes and algorithms have been developed and are readily available in the open literature. Some of the notable examples are; reactionless maneuvering algorithm [25], dual-arm coordinated control of end-effector to capture debris [26], and minimization of moments generated on satellite bus due to end-effector movement [27], etc.

3.5 Scalability of End-Effectors

Any 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 [28]. Unlike other contemporary SDR systems such as tethered-net or tethered-harpoon systems etc., the scalability of robotic systems is a well-researched area, making it possible to use phenomenological models to upscale or downscale an end-effector design with minimum loss in its target performance. This enables the design and utilization of end-effectors for capturing debris of any size. One of the seminal scalability models is Amdahl's law [29] which predicts the speedup 'S(n)' of a robotic system having 'n' parallel sub-systems. The generalized form of Amdahl's law is as follows: -

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

Numerous re-evaluations of this scalability law are available in open literature; Gustafson's Law [30] to attain optimistic estimates of speedup, and Gunther's Universal Law [31] to scale a shared-resources-based system; are a few prominent examples.

3.6 Utilization in Varying Orbits

As discussed earlier, the main candidate orbits for active SDR operations are the LEOs. In this regard, a study conducted by Maury et al.[32] indicates that the orbits of prime interest during early phases of SDR operations are between the altitudes of 750-950 km at an inclination between 82-108 degrees. However, statistical models developed to evaluate the density and scatter of debris objects [1, 33] show a rising debris population in other orbits of interest (i.e. MEOs and GEOs). Unlike LEO, the majority of debris objects in high-energy orbits are defunct satellites. For this scenario, a plethora of past research shows that end-effector mechanisms (primarily designed for capturing small to medium-sized debris) can be effectively utilized for remediation of large-sized uncooperative satellites, for which, the end-effectors are re-programmed to grasp the hooks and bars of debris-satellites and use the propulsion system of SDR spacecraft to lodge the debris-satellites into graveyard orbits [34].

3.7 Utilization with Integrated Secondary System

Compared to contemporary SDR technologies, end-effector mechanisms offer a high degree of flexibility regarding the integration of secondary systems designed for augmenting end-effectors' operational capabilities. Some possible augmentation devices include the following: -

(a) **Vision-Based Devices.** Advanced vision systems like high-speed cameras, LIDAR, depth sensors, etc. can be conveniently integrated into the end-effector. The concept demonstrator developed with current continual research (PACMAN) is a notable example where LIDAR is installed directly on the end-effector.

(b) **Passive Capture Mechanisms.** Integration of passive capturing mechanisms like adhesives, nets, and entangling wires can enhance end-effectors' grasping capability.

(c) **Safety Mechanisms**. Incorporation of active or passive safety mechanisms such as end-effector locking devices, damping mechanisms, fail-safe, etc. is readily possible.

(d) **Force and Torque Sensors.** The addition of requisite sensors on the end-effectors will provide the feedback necessary for active autonomous or semi-autonomous control.

(e) **Multi-Function Module.** The effectiveness and utility of end-effectors can be considerably enhanced by incorporating a multi-function module capable of either refining the end-effector’s capability or replacing the end-effector itself. This design will enable the end-effector to perform a variety of tasks such as capturing, grappling, cutting, and manipulating the debris object.

3.8 Magnitude & Reliability of SDR

The magnitude of SDR associated with robotic systems is relatively less (as it can capture only one debris object at a time), compared to other contemporary SDR technologies such as tethered-net or tethered-net-robot (which can theoretically capture multiple small debris at a time). However, the SDR technologies similar to net capturing mechanisms are entanglement devices that have to be disposed of along with debris objects in a practical operation. Conversely, end-effector-integrated robotic systems are reusable in nature and they can independently perform numerous SDR operations in their service life. Furthermore, robotic systems' reliability in space operations has been well-established over the last 3 decades. Thus, for a single system, the magnitude of SDR performed by robotic systems is considerably high and exponentially more reliable.

4 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 (utilization of legacy mathematical models, scalability characteristics, applicability to varying orbits, etc.) have been explored to utilize these aspects during the mission design phase and/or as 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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