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SPACE ROBOTICS FOR ORBITAL SUSTAINABILITY: ENABLING ACTIVE DEBRIS REMOVAL AND ON-ORBIT SERVICING

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ABSTRACT

The density of space debris in Earth's orbit has reached a critical stage where passive mitigation is no longer sufficient to prevent the Kessler Syndrome. Addressing the growing risk of in-orbit collisions requires a shift toward Active Debris Removal (ADR) and On-Orbit Servicing (OOS), where robotic arm missions serve as a primary technological solution for capturing uncooperative, non-functional satellites.

Robotic arms utilize multi-degree-of-freedom architectures to execute complex orbital maneuvers with high repeatable accuracy. By leveraging high structural stiffness, these manipulators can exert the necessary forces to secure large targets and manage the dynamic loads associated with orbital station-keeping or refuelling operations. Integrated force-torque sensors at the end-effector allow for precise contact management, ensuring that the capture sequence is executed without imparting destabilizing momentum to the servicer or causing structural damage to the target.

The effectiveness of these systems depends on sophisticated manipulatorcentric control laws and kinematic motion planning. Rather than relying on simple proximity maneuvers, the robotic arm must execute synchronized trajectory tracking to intercept the specific docking interfaces of a tumbling target. This involves managing the highly non-linear dynamics of a multi-link chain in microgravity, where the movement of the arm directly influences the attitude of the host spacecraft. By optimizing the arm's joint velocities and paths, the system can minimize base-reaction forces, ensuring that the robotic manipulator remains a stable and precise tool throughout the entire engagement and stabilization phase.

As the global space community moves toward a "Zero Debris" future by 2030, robotic missions represent a scalable and reliable platform for orbital maintenance. By advancing autonomous manipulation and standardizing robotic interfaces, these technologies foster a circular space economy, extending the operational life of high-value assets and protecting the orbital environment for future generations.