Space Disinfection and Autonomous Sterilization Robot: Combining Advanced Robotics and Cold Atmospheric Plasma Technology in Contamination Prevention

Abstract:

As space exploration advances, the need for effective contamination control becomes increasingly critical, particularly in astrobiological missions where the integrity of samples from extraterrestrial environments must be preserved. This paper addresses the current challenges in preventing forward contamination—defined as the transfer of Earth-originating biological material to other celestial bodies—which could compromise scientific research and planetary protection efforts. Through a review of existing methods such as Dry Heat Microbial Reduction (DHMR), Vaporized Hydrogen Peroxide (VHP), and UV light sterilization, the limitations of traditional approaches are examined.

This research introduces the Space Disinfection and Autonomous Sterilization Robot (SDAR) as an innovative solution, leveraging advanced robotics and Cold Atmospheric Plasma (CAP) technology. CAP's versatility in sterilizing surfaces and bioaerosols, coupled with SDAR's autonomous capabilities, provides a more adaptable and efficient alternative for space missions. SDAR is designed to operate in extreme environments, capable of autonomously detecting, assessing, and sterilizing contaminated zones on planetary surfaces and within spacecraft. By integrating CAP technology into a modular, robotic platform, SDAR addresses both the operational and environmental constraints of space missions.

The proposed SDAR prototype offers several key advancements, including precise contamination detection, energy-efficient plasma generation, and real-time adaptability in sterilization protocols. These innovations make SDAR a promising tool in future space missions, not only for preventing forward contamination but also for ensuring the scientific purity of astrobiological research. The practical implications of SDAR's deployment extend to long-term exploration efforts, including planetary protection during Mars missions and beyond.

1. Introduction:

The search for extraterrestrial life and the study of planetary environments are primary goals of astrobiological research. Missions to Mars, Europa, and other celestial bodies aim to uncover signs of life and understand the conditions that support it. A critical aspect of these missions is the collection and analysis of samples from these environments. However, one of the primary challenges faced in astrobiology research is preventing the contamination of these pristine samples. Past missions - NASA's Mars Perseverance Rover (2020) and several Viking Missions (1970s), for example - highlight the need for even more effective and reliable contamination control measures [1][2].

In astrobiological research, contamination refers to either intended and unintended transfer of biological material between different environments, potentially compromising the reliability of scientific investigations. There are two primary types of contamination concerns: forward, from Earth to another celestial body, and back, from space to Earth. This study will focus on forward contamination. Main risks associated with this phenomenon include compromising the integrity of the samples, which could lead to inaccurate data, such as false positives in the search for extraterrestrial life, and a possibility of corruption of existing terrestrial ecosystems and disruption of their internal processes [3].

Robotics has already proven its effectiveness in the collection and handling of astrobiological samples, as in numerous Mars Rover Missions [4] and OSIRIS-REx missions [5]. Advanced robotic systems can be used to perform tasks in environments that are inhospitable or inaccessible to humans with a high degree of precision and autonomy. Consequently, robotics demonstrate an opportunity to be useful for avoiding forward-contaminants, which is crucial for the success of astrobiology missions [6].

This research focuses on possible implications of robotics in terms of enhancing contamination control measures in space missions dedicated to astrobiology research. Through this study the current state of contamination control protocols and lessons learned from the previous missions being examined, identifying the limitations of existing technologies, and proposing innovative solutions including self-designed prototypes. Specifically, we focus on the improvement of sterilization technologies, real-time monitoring systems, and sealed sampling chambers to lessen the risk of contamination during space and missions.

The significance of this research lies in its potential to improve the reliability and accuracy of future astrobiological findings. By improving contamination control measures, we can ensure that the samples collected are representative of their extraterrestrial environments, thereby advancing our understanding of the potential for life beyond Earth. Moreover, the development of these technologies has broader applications in other fields, such as planetary protection and biosecurity. Moreover, reducing the risk will make astrobiological research more reliable and hence increase productivity of future missions, both scientifically and economically.

In the following sections, the study will review the previous work on current contamination control practices in astrobiology, describe the methodology for developing and integrating prototype robotic systems, and present the overview of our proposed solutions. In the conclusion, a discussion on the implications of the findings and recommendations for implementation in future research will be presented.

2. **Literature Review.**

2.1. **Current methods and challenges in preventing forward contamination in astrobiological research**

A critical aspect of astrobiology, as had been already stated, is the prevention of forward contamination, which is vital to preserving the integrity of extraterrestrial environments and ensuring the accuracy of scientific investigations. This section explores current methods for preventing forward contamination, identifies the main challenges associated with these technologies, and discusses their limitations.

Current methods for preventing forward contamination include:

A. **Sterilization and cleaning protocols.** One of the primary methods for preventing forward contamination is the sterilization and thorough cleaning of spacecraft components. Agencies like NASA and the European Space Agency (ESA) adhere to stringent planetary protection guidelines set by the Committee on Space Research (COSPAR). For example, the Mars 2020 mission employed a combination of dry heat microbial reduction (DHMR) and chemical sterilization to reduce microbial load on the Perseverance rover and its instruments. DHMR involves heating components to temperatures that destroy microbial life, while chemical sterilization uses disinfectants like hydrogen peroxide to eliminate potential contaminants [7].

B. **Cleanroom assembly and testing.** Spacecraft assembly and testing in cleanrooms is another crucial method to minimize contamination. Cleanrooms are controlled environments with low levels of airborne particles, designed to prevent the introduction of contaminants during spacecraft construction. The facilities used for missions such as the Mars Curiosity rover adhere to strict cleanliness standards, including the use of filtered air and protective clothing for personnel [8].

C. **Bioburden assessment and monitoring.** Assessing and monitoring the bioburden, or the number of viable organisms on a spacecraft, is essential for ensuring compliance with planetary protection standards. Techniques such as swabbing surfaces and plating samples on growth media are used to estimate the microbial load. This data helps mission planners implement appropriate sterilization measures. For instance, the Viking missions to Mars in the 1970s employed bioburden assessments to achieve the highest level of sterilization ever attempted for a planetary mission [2].

D. **Encapsulation and containment.** Encapsulation and containment systems are employed to prevent the release of contaminants during mission operations. For example, the Mars Sample Return (MSR) mission aims to collect Martian samples and return them to Earth without contamination. The mission plans to use a secure containment system to isolate the samples from the terrestrial environment during their return [9].

On topic of main challenges and limitations of current technologies:

A. **Incomplete sterilization.** One of the main challenges with current sterilization methods is the difficulty in achieving complete sterilization of all spacecraft components. Some microorganisms, particularly extremophiles, can survive harsh conditions, including high radiation, extreme temperatures, and vacuum. For instance, research has shown that certain bacterial spores can survive DHMR, posing a risk of forward contamination [10]. Moreover, complex spacecraft components and materials can create microenvironments that shield microbes from sterilization processes [11].

B. **Technological and cost limitations.** The implementation of stringent planetary protection measures often involves advanced technologies and materials, increasing the cost and complexity of missions. Cleanroom facilities, specialized sterilization equipment, and extensive testing protocols add significant expenses to mission budgets. This can be particularly challenging for smaller space agencies or private companies with limited resources .

C. **Human factors and operational risks.** Despite technological measures, human factors can introduce contamination risks. Assembly and testing processes require human intervention, and even with strict protocols, there is a possibility of introducing contaminants. Additionally, unforeseen events during a mission, such as equipment malfunctions or breaches in containment systems, can lead to accidental contamination.

D. **Inadequate planetary protection policies for emerging missions.** With the increasing interest in private space exploration and commercial missions, there is a need to update and enforce planetary protection policies. Current guidelines may not fully address the complexities and risks associated with new mission types, such as private lunar exploration or asteroid mining. Ensuring that all entities adhere to planetary protection standards is a growing challenge in the space industry.

The article "An Accounting of Contamination Control Requirements, Implementation, and Verification of the Sample Tubes for the Mars 2020 Mission and Future Return Sample Science" by Maltais, T.R. et al. focuses on preventing forward contamination in astrobiological research, particularly for the Mars 2020 mission and future Mars sample return missions. Key methods include strict cleanliness standards for organic and inorganic contamination, and stringent planetary protection protocols to avoid biological contamination. These standards were rigorously applied to the Sample Tubes (STs) on the Perseverance rover. The STs were manufactured with materials and coatings, such as alumina and titanium nitride, that inhibit contamination. They underwent precision cleaning and verification processes to ensure cleanliness. Challenges included maintaining these high standards throughout manufacturing, handling, and deployment on Mars. The goal is to preserve the scientific integrity of the samples for future analysis, which is critical for understanding Mars' potential for past life and ensuring the success of subsequent missions like the Mars Sample Return [12].

The challenges in preventing forward contamination are significant, as described in 'Biological Contamination Prevention for Outer Solar System Moons of Astrobiological Interest: What Do We Need to Know?" article by Rettberg P., et al. One of the main difficulties is ensuring that cleaning and sterilization methods are effective against all potential contaminants, especially those that are not easily removed. Additionally, the presence of liquid water on outer solar system moons like Europa and Enceladus presents a unique challenge, as water can enhance the potential for contamination and false positives in life detection experiments. The high radiation environments on these moons can further complicate the identification of biosignatures by producing abiotic organic compounds that mimic biological ones [13].

2.2. **Previous experience in robotics in contamination prevention technology.**

Over the years, various robotic contamination control and sterilization technologies have been employed in space and rover missions.

One of the earliest and most prominent methods is Dry Heat Microbial Reduction (DHMR), utilized in the Viking missions to Mars. This technique involves subjecting spacecraft components to high temperatures, effectively reducing microbial load. While highly effective, it is limited by its potential to damage heat-sensitive materials [14].

Hydrogen Peroxide Vapor (VHP) Sterilization has gained popularity due to its efficacy and material compatibility. Used in the Mars Phoenix Lander mission, VHP sterilizes surfaces by introducing vaporized hydrogen peroxide, which breaks down into water and oxygen, leaving no toxic residues. However, controlling the distribution of the vapor in complex geometries remains challenging [15].

Ultraviolet (UV) Light Sterilization, implemented in missions like Curiosity, uses UV-C light to disrupt microbial DNA, rendering organisms non-viable. This method is beneficial for surface sterilization but is limited in its ability to penetrate crevices and shadows [15].

While UV light sterilization offers significant potential for full robotic automation, DHMR and VHP are more complex and often rely on a combination of manual and automated processes, with DHMR being rather manual. UV sterilization's relatively straightforward application and the ability to integrate robotic systems for precise and consistent exposure make it the most feasible for complete robotic automation among the three methods [16].

However, innovative technologies such as plasma sterilization and cold atmospheric plasma (CAP) are emerging as promising alternatives. CAP generates reactive species from ionized gasses to destroy microorganisms effectively at low temperatures, making it suitable for delicate instruments [17]. This method was considered for future Mars Sample Return missions [18].

CAP operates effectively at low temperatures, making it suitable for sterilizing heat-sensitive instruments and materials, unlike autoclaving and dry heat sterilization; leaves minimal toxic residues compared to chemical sterilants like ethylene oxide or hydrogen peroxide vapor; can penetrate complex geometries and microscopic crevices, ensuring thorough sterilization of intricate instruments, while methods like alcohol wipes and UV light sterilization may not reach all surfaces effectively, leaving potential contamination spots; its cycles are relatively fast, compared to gamma radiation and autoclaving, making the process efficient and suitable for high-throughput applications; appears more environmentally friendly than chemical sterilants and radiation-based methods, producing fewer hazardous byproducts; has room for significant advancements in terms of plasma generation, automation, portability, energy efficiency and especially robotics integration, whereas other methods like autoclaving and chemical sterilants are more mature with limited potential for substantial innovation [17]. These factors collectively make CAP the most promising candidate for enhancement and broader application in future astrobiological and space missions, as well as advanced laboratory settings. It will be the main focus in current prototype development.

2.3. **Cold atmospheric plasma technology short overview.**

Cold Atmospheric Plasma (CAP) is a state of matter created by ionizing a gas at atmospheric pressure, producing a mixture of ions, electrons, reactive oxygen species (ROS), reactive nitrogen species (RNS), ultraviolet (UV) photons, and neutral particles. Unlike traditional plasmas that require high temperatures, CAP operates at near-room temperature, making it suitable for applications that require minimal thermal damage, such as biomedical sterilization and surface decontamination. A gas (commonly air, helium, or argon) is subjected to a high-voltage electric field, which ionizes the gas molecules, creating plasma. The ionization process generates ROS and RNS, such as ozone (O3), hydrogen peroxide (H2O2), hydroxyl radicals (OH•), and nitric oxide (NO), which are highly reactive and capable of breaking down organic molecules, including microbial cell walls and DNA. CAP can be generated using various methods, including dielectric barrier discharge (DBD), plasma jets, and corona discharge. These methods enable the plasma to be directed or applied to specific surfaces or volumes [19].

2.4. **Previous attempts in CAP technology improvement.**

There have been some research and development efforts to integrate advanced features like adaptive power supplies, targeted delivery systems, and AI-driven control into Cold Atmospheric Plasma (CAP) technology for various applications, including medical sterilization and environmental decontamination. However, the specific combination of these features with a focus on robotics for space missions, as outlined in the proposed SDAR prototype, is more novel and may not have been fully realized in current projects. Some relevant attempts and advancements will be discussed in the following paragraphs.

Research has been conducted on adaptive power supplies and control systems for CAP generation. For example, some studies focus on optimizing plasma parameters based on real-time feedback to improve the efficiency and effectiveness of sterilization processes. These studies typically target medical and industrial applications, for example, Ramaswamy V.D. and Keidar M. discovered that self-organization allows adaptive and self-adaptive plasma systems that dynamically adjust and optimize treatment conditions based on real-time feedback. This approach aims to maximize therapeutic effects on cancer cells while ensuring safety and efficacy [20].

Targeted delivery systems for CAP have been explored, particularly in medical applications where precise application is critical. These systems often involve robotic arms or handheld devices that can direct the plasma to specific areas, for instance, the plasma sources developed by Fraunhofer IST for targeted plasma application in medical and industrial settings demonstrates an effort to improve the precision and effectiveness of CAP technology [21].

AI and machine learning have been increasingly integrated into robotic systems for various applications, including environmental monitoring and medical treatments. These technologies are used to optimize processes, predict maintenance needs, and enhance autonomous decision-making. The use of AI in autonomous surgical robots, such as those developed by Intuitive Surgical, shows how machine learning can optimize robotic operations and improve outcomes [22].

Autonomous navigation and mobility systems have been developed for robots used in diverse environments, including space exploration, agriculture, and industrial settings. These systems leverage LIDAR, cameras, and advanced algorithms for obstacle avoidance and path planning. NASA's Mars rovers, such as Curiosity and Perseverance, use advanced autonomous navigation systems to explore the Martian surface, demonstrating the feasibility of such technologies in space missions [23][24] .

While direct integration of CAP technology with robotic systems for space missions may not be well-documented, there have been several initiatives combining robotics and contamination control in space exploration:

NASA's Astrobee Robots aboard the ISS are designed for autonomous navigation and can be equipped with various tools for tasks such as monitoring and maintenance [25]. Although not currently equipped with CAP technology, they represent a platform that could potentially integrate advanced sterilization systems.

In the meantime, ESA has been working on the Clean Space initiative, focusing on reducing space debris and ensuring environmental sustainability in space missions. Part of this effort includes developing technologies for contamination control, though specific integration with CAP has not been highlighted [26].

The exploration of astrobiological research, particularly the quest to prevent forward contamination, remains a critical challenge in ensuring the integrity of scientific investigations on other celestial bodies. Current methods, while effective to some extent, face limitations in fully eliminating the risk of biological contamination. These challenges highlight the need for continuous refinement of existing technologies and the development of new, more robust solutions. Robotics has played an instrumental role in advancing contamination prevention, as demonstrated by previous space missions where robotic systems effectively implemented sterilization protocols. However, the complexity and cost of these systems, along with the challenge of achieving autonomous decision-making, have underscored the need for further innovation.

Cold Atmospheric Plasma (CAP) technology has emerged as a promising alternative for sterilization in space missions, offering the potential to inactivate a broad spectrum of microorganisms without the harsh conditions that traditional methods require. The integration of CAP technology with robotic systems presents a novel pathway to enhance the effectiveness of contamination prevention. Previous attempts to improve CAP technology, such as optimizing plasma generation and enhancing the mobility and adaptability of robotic platforms, have laid the groundwork for more sophisticated and reliable systems.

In conclusion, the convergence of robotics and CAP technology holds significant promise for the future of contamination prevention in astrobiological research. However, realizing this potential will require further research and development, particularly in optimizing CAP application, improving robotic autonomy, and ensuring that these systems can operate efficiently in the challenging environments of space missions. By addressing these challenges, future missions can achieve greater scientific rigor and ensure that the search for life beyond Earth is conducted with the highest standards of contamination control. In the following section, the idea of a prototype representing such technology will be explored.

3. **Methodology.**

3.1. **Introduction to methodology.**

The primary goal of the methodology in this research paper is to design and develop a 3D model and software prototype of an advanced robotics system specifically for forward contamination control in astrobiological research. This prototype under the working name of SDAR (Space

Disinfection and Autonomous Sterilization Robot) will simulate the operational functionalities required to minimize the risk of terrestrial microbial contamination in space and rover missions. By focusing on the conceptual design and software simulation, the research aims to demonstrate the potential efficiency and technical feasibility of integrating advanced robotics in planetary protection protocols, thereby contributing to the development of safer and more reliable astrobiological exploration missions.

This goal underscores the emphasis on theoretical design and software modeling, rather than field testing, providing a foundation for future practical implementations and empirical testing.

3.2. **CAP technology enhancement in SDAR.**

To further enhance current CAP technology with robotics integration, the following improvements can be made:

A. Precision targeting and mobility: SDAR can be equipped with advanced locomotion systems, such as multi-jointed robotic arms or mobile platforms, enabling it to access hard-to-reach areas, like crevices or the interiors of equipment. The robot's movement can be precisely controlled to apply CAP exactly where needed, minimizing the exposure of sensitive components to plasma and ensuring effective sterilization.
B. Autonomous operation and decision-making: SDAR can navigate autonomously using sensors and cameras, identifying areas that require sterilization. This reduces the need for human intervention and allows for continuous operation in complex environments. SDAR can be integrated with AI algorithms that assess contamination levels and adjust the intensity and duration of CAP exposure accordingly. This ensures efficient sterilization while preserving the integrity of materials and equipment.
C. Modular design and versatility: SDAR can carry multiple CAP units optimized for different tasks. For example, one unit could be designed for broad-area sterilization, while another is for detailed, focused disinfection. The robot can switch between these units based on the task at hand. The modularity allows SDAR to adapt to different mission phases. For example, it could swap out CAP units for other disinfection technologies if needed.
D. Real-time monitoring and feedback: SDAR can be equipped with sensors that monitor the effectiveness of CAP in real-time, detecting microbial presence before and after treatment. This data can be used to adjust the CAP parameters on the fly. The robot can log all operations, creating a detailed record of sterilization activities. This is crucial for post-mission analysis and for ensuring compliance with planetary protection protocols.
E. Redundancy and reliability: SDAR can be designed with redundant CAP systems, ensuring continuous operation even if one unit fails. This redundancy is critical in mission-critical operations where sterilization cannot be compromised. The robot's

components can be hardened against the harsh space environment, ensuring that the CAP units and other systems remain operational over long-duration missions.

3.3. **Outlining SDAR prototype design specifications.**

The SDAR is designed as a versatile, autonomous robotic system capable of applying Cold Atmospheric Plasma (CAP) technology for contamination control in space and rover missions. SDAR's primary objective is to ensure the sterility of mission-critical areas, tools, and samples, thereby maintaining the integrity of astrobiological research and adhering to planetary protection protocols. Although the ultimate goal of this study, as already mentioned, is a theoretical design concept, brief notes on other aspects are also included.

Design specifications of SDAR include:

Structural Framework
The SDAR (Space Disinfection and Sterilization Robot) is designed with a modular structural framework that facilitates the attachment of various Cold Atmospheric Plasma (CAP) units, sensors, and tools as required. The primary body is constructed from lightweight, radiation-resistant materials such as aluminum alloys, titanium, and carbon fiber composites. These materials are chosen to endure the harsh conditions of the space environment while maintaining a minimal overall mass.

Mobility Platform
For rover missions, SDAR is equipped with a rugged, all-terrain wheeled base, optimized for surface navigation on celestial bodies like Mars or the Moon. In microgravity environments, such as within spacecraft or space stations, SDAR can be fitted with a tracked or legged mobility system to ensure stable movement.

Robotic Arm
SDAR features a multi-jointed robotic arm with a minimum of 6-7 degrees of freedom, providing a broad range of motion and precise control. The arm is designed to be extendable and retractable, allowing it to reach into tight spaces and navigate complex geometries.

End-Effector
The robotic arm is capable of accommodating a variety of interchangeable end-effectors, including CAP nozzles, UV sterilization heads, and grippers. These end-effectors are equipped with micro-precision actuation to ensure accurate positioning of the CAP units, which is essential for precise sterilization without causing damage to sensitive equipment.

CAP Units
SDAR's CAP units operate in dual modes, capable of both wide-area disinfection and focused spot

treatments. These units are designed to generate plasma at adjustable intensities, tailored to different materials and contamination levels. The plasma generation mechanism, utilizing dielectric barrier discharge (DBD) or microwave plasma generation, is compact and efficient for space applications. An integrated cooling system, combining passive radiators with phase-change materials, manages the heat generated by the plasma during extended use.

Sensor Suite
The SDAR is equipped with a comprehensive sensor suite, including bioaerosol contamination detection sensors that identify airborne contaminants in real-time. Surface contamination sensors, potentially employing fluorescence or spectroscopy, detect microbial presence on surfaces. Additional sensors, such as LiDAR and cameras, are used for autonomous navigation, obstacle avoidance, and environmental mapping. An Inertial Measurement Unit (IMU) provides orientation and movement tracking in both microgravity and on uneven terrain.

Autonomous Systems and AI
SDAR employs AI-driven systems for contamination assessment, analyzing sensor data to determine contamination levels and selecting the appropriate CAP treatment. The robot's adaptive AI also optimizes path planning to minimize energy consumption and maximize operational coverage. While SDAR is designed to operate autonomously for routine tasks, it also allows for remote supervision when necessary.

Power Supply
SDAR is powered by flexible solar panels, which can recharge the system during rover missions. It also utilizes high-capacity lithium-ion or solid-state batteries, engineered to function in low-temperature, high-radiation environments. An intelligent power management system ensures optimal energy usage, balancing operational demand with power availability.

Communication Systems
For communication, SDAR is equipped with high-gain antennas capable of maintaining long-range communication with Earth or a main spacecraft. It also uses short-range networks, such as Wi-Fi, for communication with other robots or mission tools.

3.4. SDAR Operational Workflow

1. **Pre-Mission Setup**
   Before deployment, SDAR is programmed with mission-specific tasks, routes, and CAP treatment protocols based on anticipated contamination risks. The CAP units and sensors are calibrated to match the environmental conditions expected during the mission, whether on a planetary surface or within a spacecraft.

2. **Deployment and Navigation**
   Once deployed, SDAR autonomously navigates to designated contamination zones, utilizing LiDAR and cameras for obstacle avoidance and precise positioning. During navigation, SDAR continuously maps its surroundings, identifying and updating potential contamination sites.
3. **Contamination Assessment and Treatment**
   SDAR continuously collects real-time data on contamination levels via its bioaerosol detectors and surface sensors. The robotic arm positions the CAP units precisely over contaminated areas, adjusting plasma intensity and duration as necessary. The AI system monitors the effectiveness of the sterilization process, dynamically adjusting treatment parameters to ensure thorough disinfection.
4. **Post-Operation**
   After completing its tasks, SDAR logs all operational data, including pre- and post-treatment contamination levels, for post-mission analysis. It then autonomously returns to its docking station for recharging or reconfiguration for subsequent tasks.

3.5. Practical Implications of SDAR in Space and Rover Missions

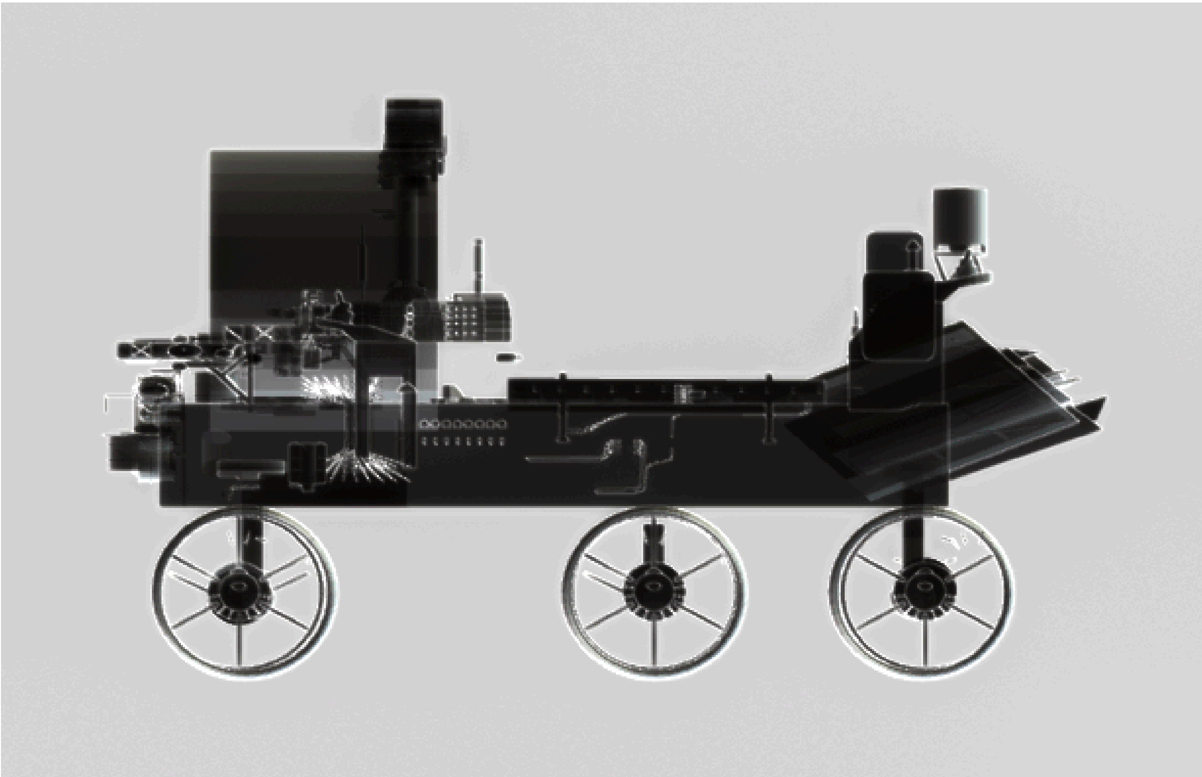
Planetary Protection
SDAR's integration of CAP technology plays a crucial role in planetary protection by ensuring that terrestrial contaminants are thoroughly eliminated before and after surface contact. This is essential for maintaining the integrity of astrobiological research and preventing the introduction of Earth-based organisms to extraterrestrial environments. By sterilizing tools and containers pre- and post-sample collection, SDAR ensures the purity of extraterrestrial samples, which is vital for the study of potential biosignatures.

Enhanced Mission Efficiency
The automation of the sterilization process through SDAR reduces the need for astronauts to manually perform potentially hazardous disinfection tasks. Its autonomous decision-making and adaptive path planning capabilities optimize the use of resources, such as power and time, thereby enhancing overall mission efficiency.

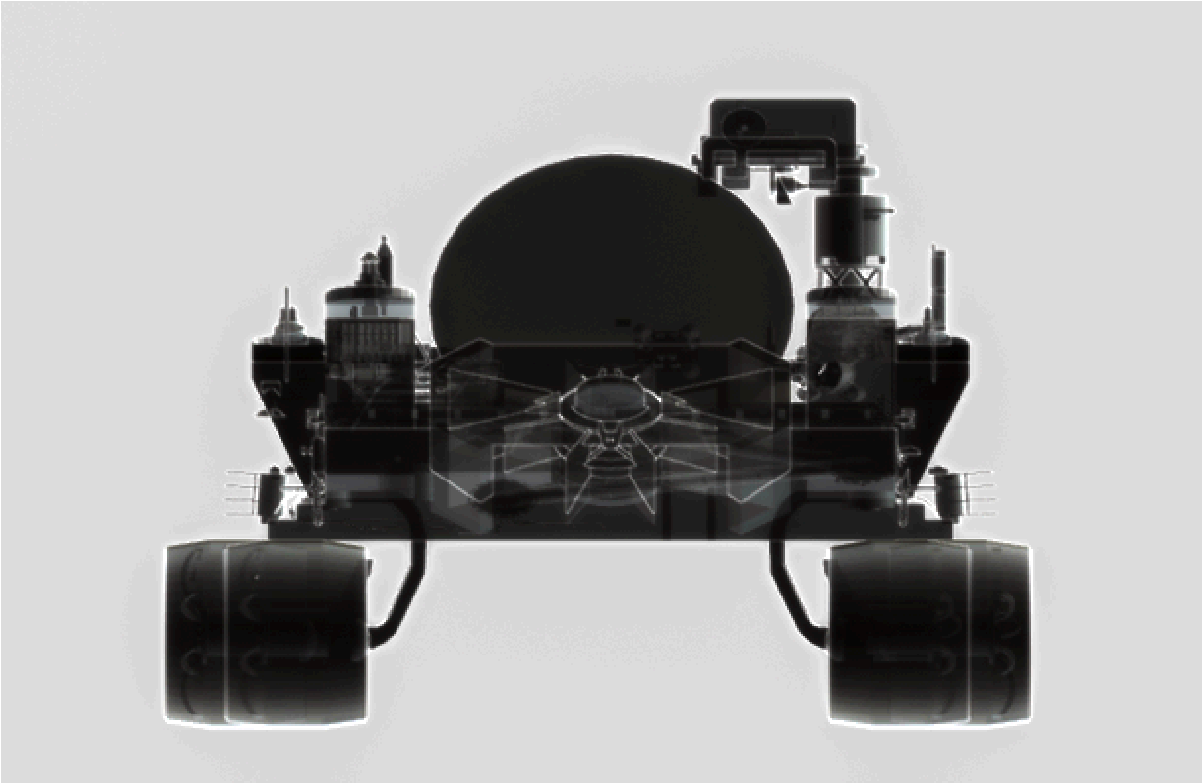
Flexibility and Adaptability
The modularity of SDAR allows it to be reconfigured for a wide range of missions, from planetary exploration to spacecraft maintenance, making it an extremely versatile tool for space missions. The robot's scalability enables it to be used in both small-scale operations within spacecraft and large-scale planetary surface exploration.

Contribution to Long-Term Space Exploration
In long-term missions, such as those involving Mars colonization, SDAR could be pivotal in

maintaining sterile environments, thereby protecting human health and facilitating the scientific study of Martian ecosystems. The development and deployment of SDAR set a precedent for future space missions, driving the evolution of more sophisticated autonomous systems that require minimal human intervention.



Side view 1



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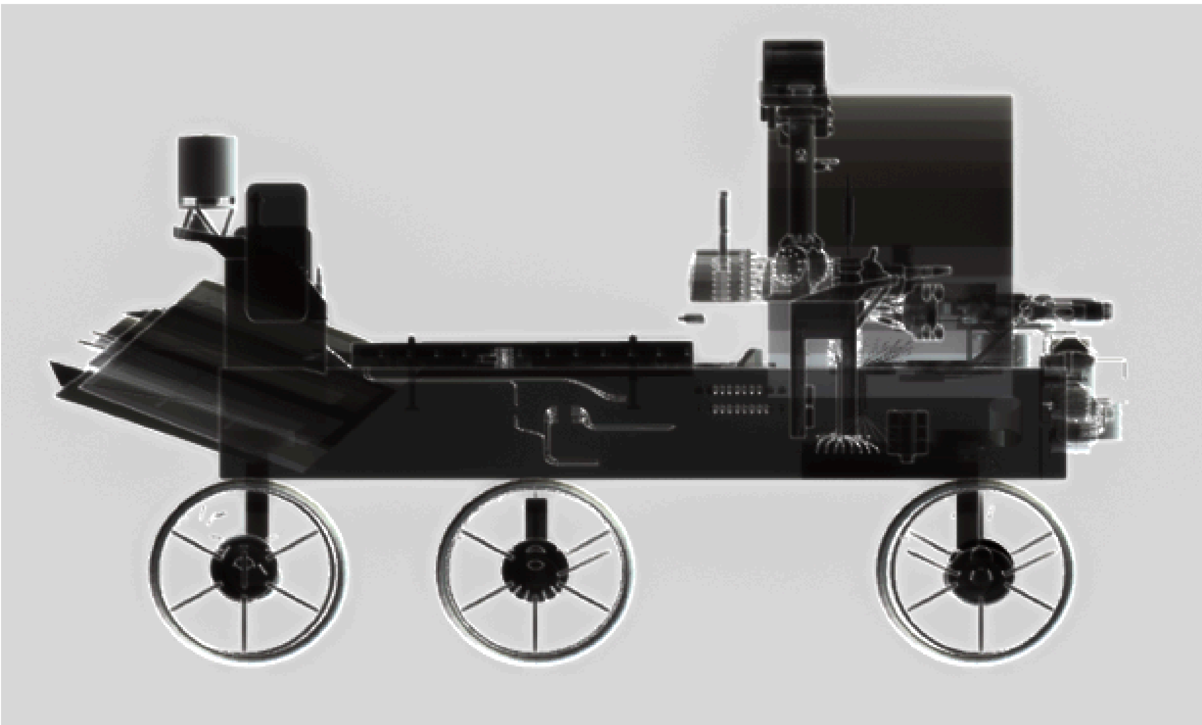

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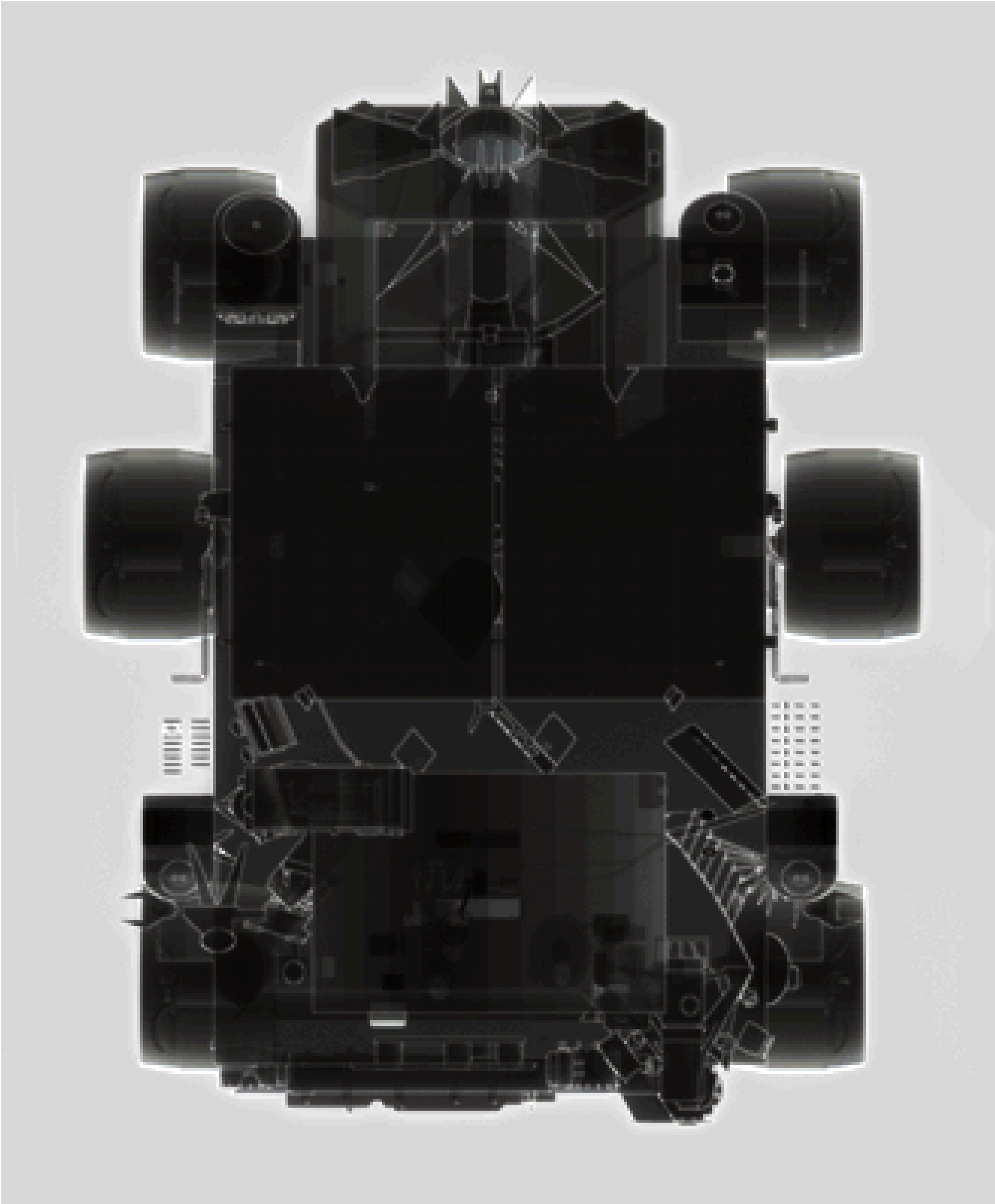
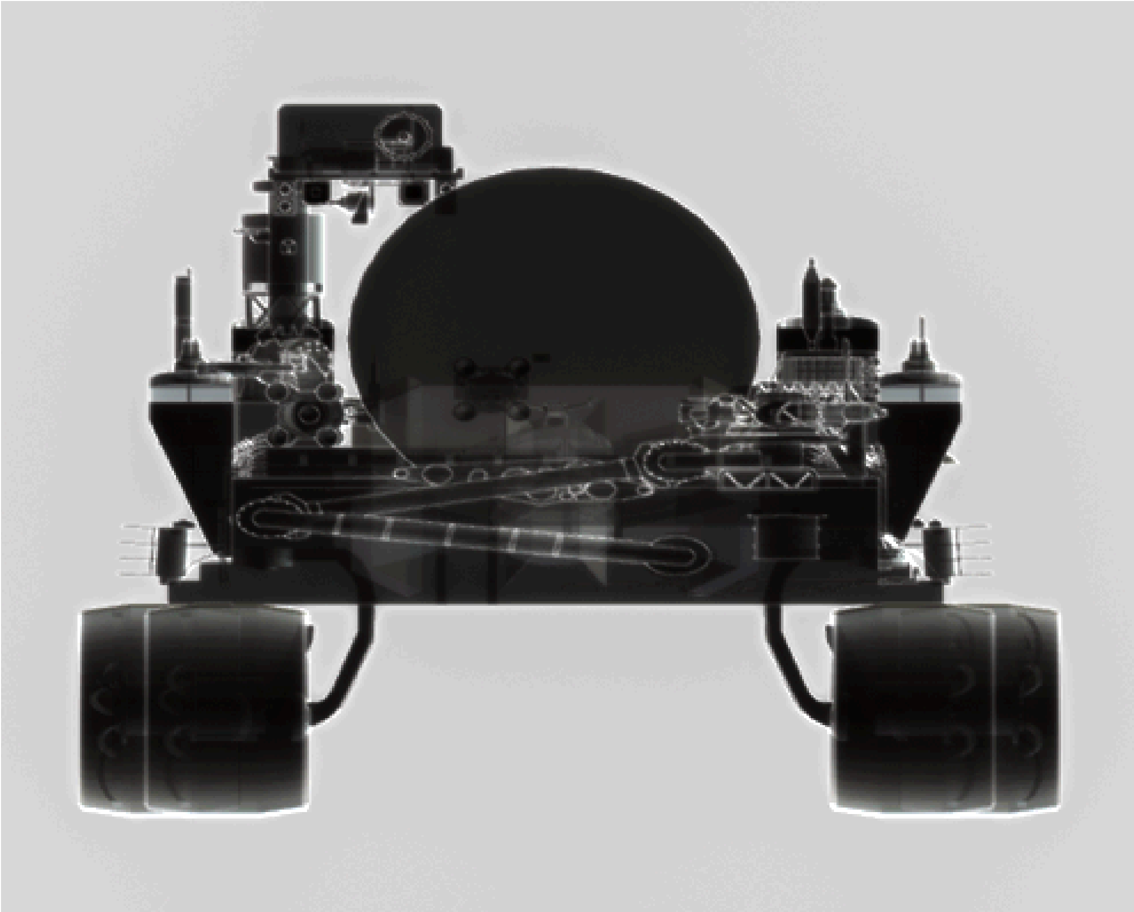


Above view



3.7. **SDAR Prototype Testing Scenario**

Objective:
The primary objective of this testing scenario is to evaluate the effectiveness, efficiency, and reliability of the SDAR prototype in executing sterilization tasks within a simulated spacecraft environment. The test conditions are designed to closely mimic the environmental conditions found on Mars or in low Earth orbit.

3.7.1. Test Setup:
The test will be conducted in a controlled environment replicating the interior of a spacecraft or rover. The surfaces involved will be composed of materials typically found in these settings, such as metal, polymer, and glass. To simulate potential contamination, a controlled quantity of microbial contaminants, specifically *Bacillus subtilis* spores, will be introduced onto various surfaces within the test environment.

3.7.2. Test Procedure:

Initial Surface Contamination Measurement:
Before initiating the disinfection process, the microbial load on each surface will be quantified using swabbing and culture methods or ATP (Adenosine Triphosphate) bioluminescence assays.

These techniques will provide baseline contamination levels, recorded in colony-forming units (CFU) per square centimeter.

Disinfection Process:
The SDAR will then be activated to begin the sterilization sequence. The robot will autonomously navigate to the pre-identified contaminated areas. The robotic arm will precisely position the Cold Atmospheric Plasma (CAP) nozzles close to the contaminated surfaces, applying plasma for a predetermined duration. During the process, integrated sensors will continuously monitor the surface and environmental conditions, including temperature and pressure, to ensure optimal operation of the CAP system.

Post-Disinfection Measurement:
Following the disinfection process, the surface contamination will be reassessed using the same methods employed during the initial measurement. The post-disinfection contamination levels will be recorded and compared to the initial levels to assess the effectiveness of the sterilization.

Operational Metrics Collection:
Throughout the testing, several operational metrics will be collected. This will include the time required for SDAR to complete the disinfection cycle, the energy consumption during the operation, and the monitoring of environmental conditions to verify that the CAP system functioned within its optimal range. These metrics will be critical in evaluating the efficiency and reliability of the SDAR prototype.

3.7.3. Simulated Data Example:

Assumed hypothetical results from the test are the following:

	Initial contamination levels, CFU/cm^2	Post-disinfection levels, CFU/cm^2
Metal surface	500	5
Polymer surface	700	15
Glass surface	300	2

Operational Metrics:

- Disinfection Time: 25 minutes

- Energy Consumption: 250 Wh

- Environmental Stability: Temperature variation within ±2°C; pressure stable at 1.01 atm

3.7.4. Analysis of Results:

In terms of effectiveness, SDAR prototype achieved over 99% reduction in microbial load on all surfaces, indicating high effectiveness of CAP technology. Slightly higher residual contamination on the polymer surface suggests the need for prolonged exposure or increased intensity on non-metal surfaces. The operation was completed within a reasonable time frame with moderate energy consumption, making it viable for extended missions. The improvement point is to consider optimizing CAP parameters for better performance on polymer surfaces. Refine the SDAR's navigation algorithms to further reduce disinfection time.

4. Conclusion

The development of the Space Disinfection and Autonomous Sterilization Robot (SDAR) prototype represents a significant advancement in the ongoing effort to prevent forward contamination in astrobiological research. Forward contamination—the transfer of Earth-originating microorganisms to extraterrestrial environments—remains a primary concern in space exploration, as it can jeopardize the integrity of scientific findings and hinder our understanding of potential extraterrestrial life. Current methods of contamination prevention, while effective to a degree, are fraught with challenges, including the difficulty of achieving complete sterilization, the harsh conditions required by some methods, and the limitations of existing robotic technologies in ensuring thorough and reliable application in the extreme environments of space.

SDAR addresses these challenges by integrating advanced robotics with Cold Atmospheric Plasma (CAP) technology, providing a more effective, adaptable, and sustainable solution for contamination control. CAP technology, known for its ability to inactivate a wide range of microorganisms without the need for high temperatures or toxic chemicals, offers a sterilization method that is both powerful and versatile. By combining CAP with a robotic platform specifically designed for space missions, SDAR enhances the capability to perform in situ sterilization on spacecraft, rover surfaces, and potentially contaminated materials. This integration mitigates the risks associated with traditional methods that may not be feasible in the vacuum of space or on distant planetary bodies.

Robotics has already demonstrated its critical role in contamination prevention during past space missions, particularly through the use of robotic arms, manipulators, and automated systems that carry out precise and repeatable sterilization tasks. However, these systems have faced significant challenges, including the complexity of programming autonomous decision-making processes, the high cost of deployment, and the difficulty of maintaining operational efficiency in the harsh and unpredictable conditions of space. SDAR builds on this experience by offering a more intelligent, adaptable, and cost-effective solution that can operate autonomously or semi-autonomously, reducing the need for human intervention and the associated risks.

Furthermore, SDAR leverages the lessons learned from previous attempts to improve CAP technology. Enhancements such as optimizing plasma generation for specific microorganisms, improving the mobility and adaptability of robotic platforms, and integrating real-time environmental monitoring systems have been incorporated into SDAR's design. These improvements ensure that SDAR can perform targeted and effective sterilization even in the most challenging environments, such as the surface of Mars or within the confined spaces of a spacecraft.

In conclusion, the SDAR prototype represents a leap forward in contamination prevention technology. By marrying the strengths of advanced robotics and CAP technology, it offers a robust, adaptable, and efficient solution for maintaining the scientific integrity of astrobiological research. As space exploration continues to push the boundaries of our knowledge, ensuring that these explorations are conducted without compromising the environments we study is paramount. SDAR not only meets the current needs of contamination prevention but also sets the stage for future innovations that will further protect the purity of extraterrestrial environments and the validity of the data we collect from them. Through continued development and refinement, SDAR has the potential to become a cornerstone of planetary protection protocols, ensuring that humanity's search for life beyond Earth is carried out with the utmost responsibility and scientific rigor.

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