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# Solution Printing of Electronics and Sensors: Applicability and Application in Space

*Weibin Li,* Chen Zhang, Ding Lan, Wenjie Ji, and Yuren Wang**

**To ensure the safety and reliability of increasingly frequent, long-duration, and long-distance space missions, a sufficient and timely supply of the electronics and sensors that are essential in the maintenance and regeneration of spacecraft in space has become urgent. Solution-based printing (SP) in space can be considered a disruptive technology for in situ manufacturing and maintenance of functional devices during the long duration and endurance of space exploration and crewed spaceflight. Herein, the origin and overview of the printing techniques in space are first introduced and further the printing processes in extreme space environments are discussed; then, its potential space applications in flexible solar cells, soft and wearable sensors, and space-based antennas are forecast; finally, survivability for printed electronics in space is analyzed. Overall, a comprehensive description of the applicability and application of the SP techniques for manufacturing electronics and sensors in space is given.**

## 1. Introduction

Electronics are critical in information transmission, energy supply, and health management in space exploration.[1–3] However, these electronic devices and sensors always face unexpected failures and inevitable wastage under extreme and adverse environments in space; therefore, a large number of spare and repair parts are required for consumption and maintenance in orbit. The current strategy for the supply of electronics in space is through ground-based microfabrication and subsequent rocket delivery, as shown in **Figure 1**. However, it is difficult to realize the timely and in situ supply of functional devices in outer space using this strategy due to the constraints of time efficiency, volume, and launch cost of the space vehicles. For long-duration manned missions in low Earth orbit like the International Space Station (ISS), 3000 additional spares should be delivered to support the consumption and maintenance for the healthy and stable operation of the ISS annually; in addition, ≈13 000 and 18 000 kg of spares are maintained on orbit and on the ground for operation of the ISS, respectively, which have resulted in huge cost and consumption.[4] The underlying reason lies in the difficulty to predict which components will be damaged and when the device failure will occur. For long-endurance missions such as Mars, it takes 6–9 months for one-way trips far from Earth; therefore, the timely resupply of spare parts by relying on the mass launch from Earth on this large spatiotemporal scale seems impossible. It means that the capability of in situ manufacturing for maintenance and refurbishment of electronics in spacecraft far away from the Earth becomes paramount. Therefore, there has been a paradigm shift for the supply and maintenance of electronics and functional devices in recent years, changing from conventional mass launch on Earth toward in situ manufacturing in space.[5]

The in-space manufacturing capability is of great significance for space exploration, making it possible to promptly supply and maintain functional electronics and sensors in situ. Electronics fabrication on the ground relies on the top-down approach of conventional lithography techniques, which requires sophisticated and expensive equipment, high levels of cleanliness, and complicated processes.[6,7] The traditional fabrication approach can be difficult to expand into space due to the limited resources, considerable cost, and the extreme environment in space. An alternative concept is a bottom-up technique in which functional solutions or inks can be simply and directly printed on the substrate to fabricate patterned films by the way of additive manufacturing. This well-known solution-based printing (SP) approach, which covers multitudinous solutions and substrates, is currently a commercialized manufacturing technology for fabricating electronics. Compared with lithographical techniques, printing techniques have many advantages including simple processes, high efficiency, good compatibility for substrates, and extremely low costs. SP has yielded unusually brilliant results in the fabrication of flexible and large-area electronics on Earth,[8] such as organic light-emitting diodes (OLEDs),[8–10] radio frequency identification devices (RFIDs),[11–13] soft sensors,[14,15] etc. All these advantages make the printing technique a feasible and applicable strategy for manufacturing electronics in space.

As an additive manufacturing technology, the SP can realize personalized and made-on-demand electronics in space. The capability of printing electronics and sensors in space on-demand could not only assist in reducing the launch mass

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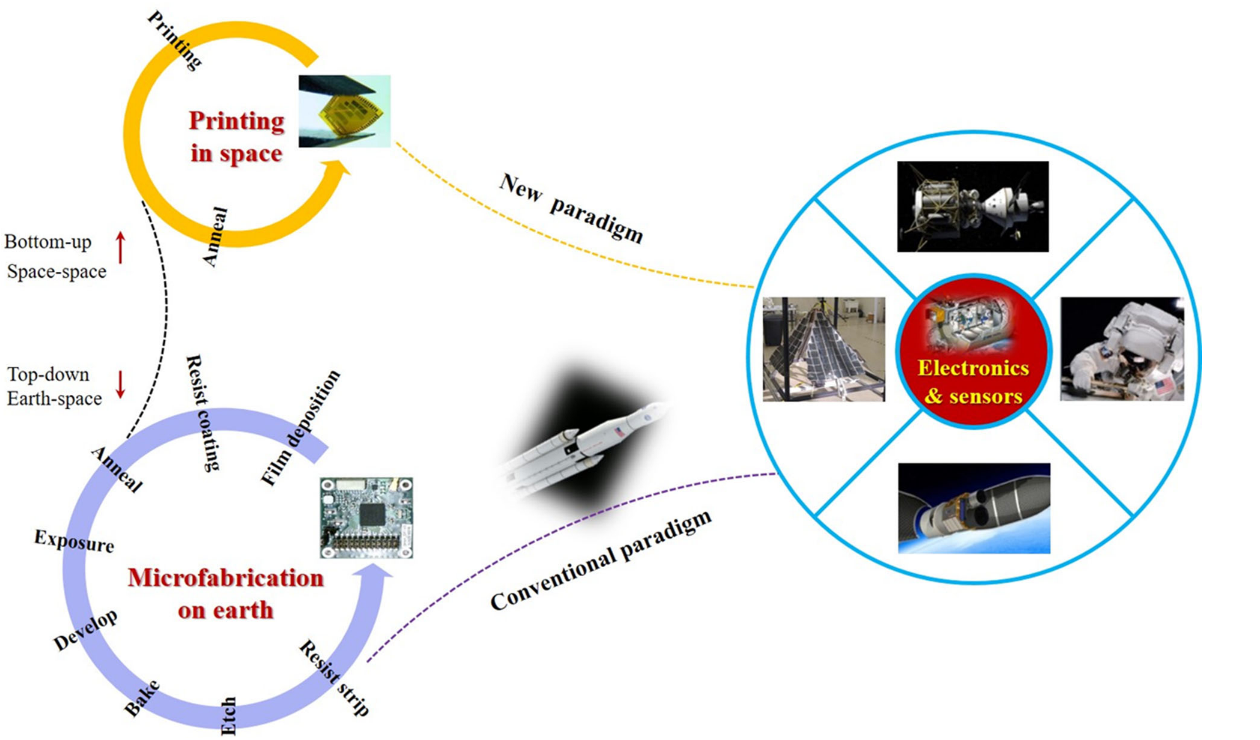



**Figure 1.** The new and conventional way of supply and maintenance of electronics and sensors in space. A new way is a bottom-up approach of SP in space directly (the yellow circle), while the conventional way is a two-step strategy: top-down approach of microfabrication on Earth and then reaching space by rocket transportation (the purple circle). These electronics and sensors have a wide range of application scenarios in space, such as advanced spacecraft, human–machine interfaces, and solar power systems. Image courtesy of NASA.[108]

(extra spares) for long-duration and long-endurance missions but also enhance safety by helping crews deal with unexpected situations in extraterrestrial space. In addition, the SP enables scalable and continuous roll-to-roll (R2R) production of electronics, which may create a huge opportunity to fabricate flexible, high-quality, and large-area functional films in space, such as flexible photovoltaic cells. The research and application of SP techniques for electronics on Earth have been relatively mature and extensive, which can be referred to several excellent reviews in recent years.[16–18] However, the applicability and application of the SP in space (SPS) is still in its infancy; opportunities and challenges coexist in the future.

Here, we expect to convey an overview of the applicability and application of the SPS for the fabrication of electronics and sensors. We will present the SPS from the following four aspects: 1) origin and overview of the SPS; 2) printing processes in extreme space environments; 3) potential space applications of the printed electronics; and 4) survivability for printed electronics in space.

## 2. Origin and Overview of the SPS

### 2.1. Origin of the SPS

SP can be traced back to traditional woodblock printing before 220 AD in the Tang Dynasty of China; in the next two thousand years that followed, it promoted the development of the scientific revolution and laid the material basis for the spread of culture and civilization. Over the past few decades, traditional printing techniques have been combined with functional solutions to fabricate organic semiconductors,[19] flexible sensors,[20] and photovoltaic cells,[21] which led to the rise of printed electronics. Before long, printed electronics has been introduced into space exploration, in which one of the most striking examples comes from NASA; it proposed the concept of printable spacecraft to investigate the viability of printed electronics for creating multifunctional spacecraft platforms in 2012, which is possible to totally transform the way of building spacecraft.[22]

With the increasing requirements of on-orbit safety and maintenance in recent years, the in situ printing of components and spare parts in space has attracted widespread attention.[23–25] In 2014, NASA developed a phased technology roadmap for space manufacturing before 2050, in which electronics manufacturing was listed as one of the important technical directions.[26] However, in situ SPS is still in the proof-of-concept stage. To explore multimaterial and on-demand manufacturing of electronics for sustainable exploration missions, NASA Marshall Space Flight Center (MFSC) designed a multifunctional nScrypt printer, which could precisely print polymer-based substrates and dispense electronic inks in desired patterns, and a series of functional components including printed sensors have been demonstrated on Earth.[26] In another funded program, aerosol jet printing was adapted and miniaturized by Optomec for additive manufacturing of electronics under a microgravity environment.[4] In China, a colloidal solution was chosen as a model system to verify the key processes related to SPS in microgravity aboard the SJ-10 satellite in 2016, in which the control and transfer of colloidal suspensions were tested; the drying process of the printed patterns was studied.[27,28] In 2017, the Graphene Flagship, in collaboration with the European Space Agency (ESA), conducted several microgravity experiments in parabolic flights and rocket launches to test the possibilities of printing graphene inks in space.[29] These ground-based testing and microgravity studies make the capabilities of in situ printing for electronics and sensors in space possible.

### 2.2. Overview of the SPS

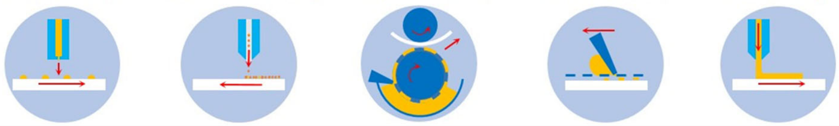
Many conventional 2D printing techniques have the potential to be extended to space. We briefly introduce the classification and characteristics of these technologies which have already been reviewed comprehensively in the past.[18,30] These SP technologies can be divided into digital and template printing, as shown in **Figure 2**. For digital printing, the information of the pattern is in the digital form that directs a nozzle to deposit functional solutions onto the moving substrate, which include two general methods of inkjet printing[31] and aerosol jet printing.[32] Gravure printing[33] and screen printing[34] are two typical template methods, which rely on a master or template to print patterned film. Both template methods can be accomplished in an R2R manner for large-scale manufacturing.[35,36] In addition, some coating methods (such as slot-die coating and dip coating) are also viewed as a printing process that can make continuous prints.[37] However, it is beyond the scope of this section. Different approaches have their specific range of printing parameters, such as solution viscosity, high resolution, film thickness, and printing speed, as shown in Figure 2. For example, highly viscous solutions are better adaptable for screen printing, while not suited for inkjet printing, because it can easily result in nozzle clogging. However, the solutions have a wider range of viscosity for aerosol jet printing and gravure printing. Therefore, it is necessary to match the application scenarios according to the characteristics of these printing technologies.

Recently, with the rapid development of additive manufacturing technology, printed electronics convert from conventional 2D to rising 3D, which paved the way in new fields of electronics fabrication.[38–40] The rheological characteristics of the solutions for 3D printing are far more viscous than 2D printing. These solutions are always yield stress fluid that exhibits shear-thickening behavior. More in-depth studies on the basic relationship between solution rheology and the 3D printing process are available in the review of Zhu et al.[41] 3D printing of diverse materials has been used for manufacturing functional components such as quantum dot-based LED (QD-LEDs) (**Figure 3**a)[42] and soft strain sensors (Figure 3b).[43] In 2013, a CubeSat Trailblazer was launched that includes a 3D-printed subsystem integrated with the circuitry of conductive inks, which aims to test the use of printed devices and electronics exposed in a harsh environment; the integrated circuitry within a structural element can be seen in Figure 3c,d.

To print diverse electronics and sensors, different types of functional solutions, including conductors,[44–46] semiconductors,[17] dielectrics,[47] and composite materials,[48] need to be prepared.[17] According to application requirements, the chosen substrate can be low cost, optically transparent, flexible, or biocompatible. For example, polydimethylsiloxane (PDMS) is by far the most common substrate for fabricating soft and stretchable electronics due to its flexibility and biocompatibility. Given the above, the printing techniques, solutions, and substrates should be well matched under proper processes based on the application scenarios of printed electronics.

## 3. Printing Processes in Extreme Space Environments

The environmental differences between the ground and space are both challenges and opportunities for the printing processes; these differences should be carefully considered in different



| Printing Techniques / Printing Characteristics | Inkjet Printing | Aerosol Jet Printing | Gravure Printing | Screen Printing | 3D printing |
|---|---|---|---|---|---|
| Solution viscosity (cP) | 10-20 | 1–2500 | 10-1000 | 500-5000 | Very high (viscoelasticity) |
| High resolution (μm) | < 30 | 10-200 | 5-100 | 50-150 | < 100 |
| Film thickness (μm) | 0.005–0.5 | 0.1–5 | 0.1-1 | 5-100 | 25-50 |
| Printing Speed (m/s) | < 5 | < 0.2 | < 10 | < 1 | $\sim 10^{-3}$ |
| Scalability | Limited | Limited | R2R | R2R | No |
| Dimensionality | 2D | 2D | 2D | 2D | 3D |
| Patterning Type | Digital patterning | Digital patterning | Template patterning | Template patterning | Digital patterning |

**Figure 2.** Characteristics of different SP technologies: inkjet printing, aerosol jet printing, gravure printing, screen printing, and 3D printing.[18,109,110]

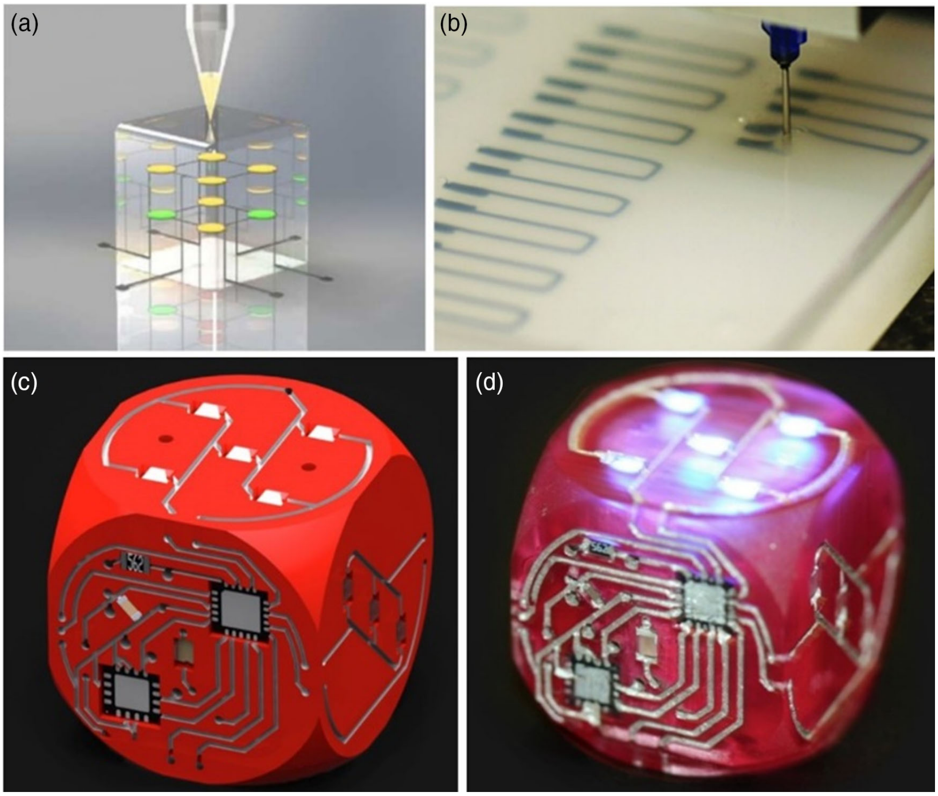



**Figure 3.** a) 3D printing of QD-LEDs. Reproduced with permission.[42] Copyright 2018, American Chemical Society. b) Schematic of an embedded 3D printing process in making soft sensors. Reproduced with permission.[43] Copyright 2014, Wiley-VCH. c,d) 3D-printed structures with integrated circuitry of conductive inks. Reproduced with permission.[111] Copyright 2014, IEEE.

space scenarios, including gravity variation (Zero-g for the planetary orbit, 1/6 g for the Moon, and 1/3 g for the Mars), vacuum, extreme temperature fluctuations, and ionizing radiation.[49] Studies of influences of the space environment on these printing processes help in the management and recycling of solutions and controllable printing of high-quality films. The SP technique involves two common and key processes, solution transfer and liquid solidification, which are closely related to the gravity level and can also be influenced by vacuum and temperature. To analyze these dominating factors in the general printing process, we mainly focus on microgravity effects on the solution transfer and liquid solidification in this section. Considering extravehicular printing, the influences of vacuum and temperature fluctuations on the printing processes are additionally introduced, as shown in **Table 1**.

### 3.1. Microgravity Effects

Evaluating the effects of gravitational change on printing processes is essential for the success of the SPS. This is because the SP process essentially involves numerous fluid mechanical phenomena that are extremely sensitive to gravity. Studies have shown that the effects of buoyancy convection, sedimentation, and pressure gradient that always exist in printing processes on Earth will be greatly weakened and even vanished under microgravity conditions.[50] Therefore, the transfer and solidification of solutions in SP can be greatly affected by these effects under microgravity conditions, which will be further discussed.

#### *3.1.1. Transfer of Solutions*

In the SP process, liquid solutions need to be transferred toward the substrate through the form of the liquid bridge, droplet, and liquid meniscus, as shown in **Figure 4**a–c. Although these printing forms are very different, the evolution of the liquid–air interface, moving contact line (MCL), and dynamic rheological behavior are common challenging problems of liquid transfer in printing processes. For printing guided by the liquid bridge (such as gravure printing, as shown in Figure 4a), it experiences a combination of shear, extension, and rotation due to relative motion between the gravure cell and web, in which MCL plays a key role. Gravity has an impact on the evolution of the interface shape and the MCL, for example, the gravitational forces can lead to appreciable sagging of non-Newtonian fluids for a liquid bridge, while the deployment and stretching of the liquid bridge are stable and controllable in microgravity (Figure 4d).[51] For droplet-based printing (such as inkjet printing,[52] as shown in Figure 4b), the solutions transfer through jetting of the droplets from the nozzle, in which the spreading and wetting behavior of the droplet on the solid surface vary with acceleration of gravity, which will influence the MCL and the droplet shape.[53–55] To meniscus-guided printing (such as dip coating, as shown

**Table 1.** Influences of the extreme space environment (microgravity, vacuum, and temperature fluctuations) on the printing processes of solution transfer and liquid solidification. "√" and "×" represent pros and cons for the SPS, respectively.

| Extreme environment in space | | Printing process | |
|---|---|---|---|
| | | Solution transfer | Liquid solidification |
| Microgravity condition | | Unmanageable liquid climbing [×] | No buoyant convection and solutes sedimentation, uniform environment [√] |
| Extravehicular vacuum | | Flash evaporation [×] Evaporation freezing [×] | Flash evaporation crystallization [√] Evaporation freezing [×] |
| Extreme temperatures fluctuations | High | Thermal evaporation [×] Thermal convection mixing [√] | Thermal evaporation [√] Uncontrollable thermal convection [×] |
| | Low | Low-temperature freezing [×] | |

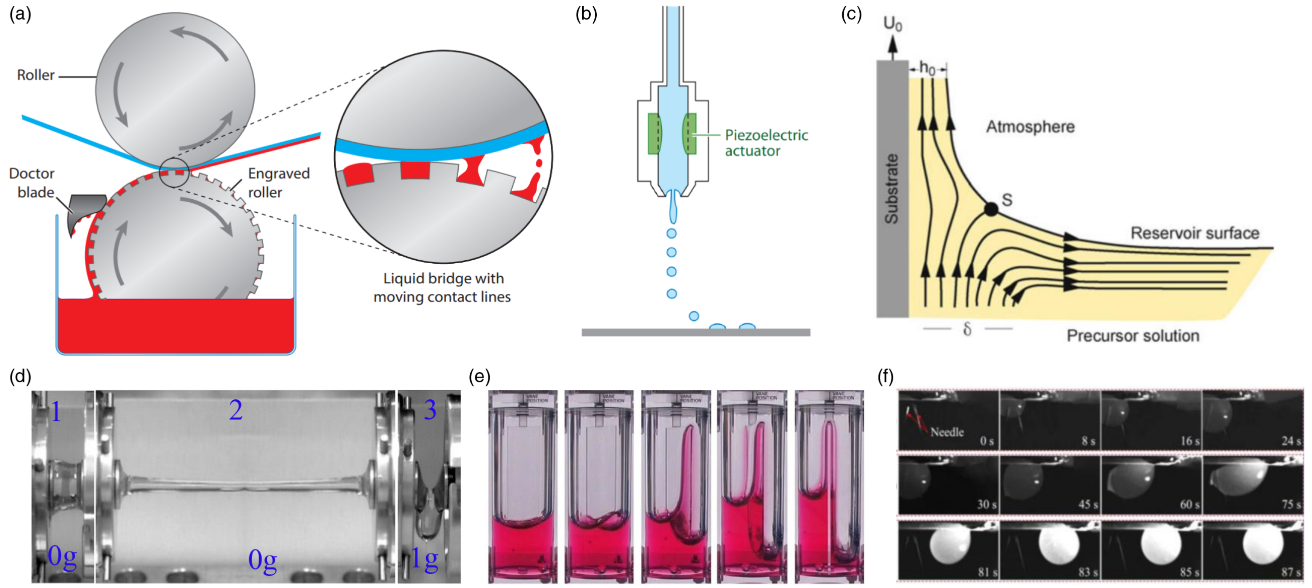



**Figure 4.** Schematic of solution transfer through forms of the liquid bridge, droplet, and liquid meniscus as examples of a) gravure printing, b) inkjet printing, and c) dip coating, respectively. a) Reproduced with permission.[112] Copyright 2015, Annul Reviews. b) Reproduced with permission.[113] Copyright 2010, Annul Reviews. c) Reproduced with permission.[114] Copyright 2013, Springer. d) Demonstration test of rheological behaviors of polymer solutions in microgravity: fluid deployment in 0 g (1); stretching of a polymeric liquid bridge in 0 g (2); and fluid sagging in 1 g (3). Reproduced with permission.[51] Copyright 2006, AIAA. e) The capillary flow, interface evolution, and contact line dynamics under microgravity conditions. e) Reproduced with permission.[60] Copyright 2009, Elsevier. f) Liquid transfer from printer needle on a patterned substrate: colloidal droplet generation, separation, and oscillation in microgravity. Reproduced with permission.[64] Copyright 2018, American Chemical Society.

in Figure 4c), gravity competes with viscous forces and surface tension, and the balance of those forces will determine the meniscus configuration and hence the film thickness.[56] The above analysis means that the efficient control of the fluid interface, MCL, and flow behavior in the solution transfer process under microgravity will be essential for the success of the SPS.[57]

Without the influence of gravity, solution transfer is under the cooperative effect of the surface tension, the viscous force, and the inertial force in microgravity conditions. Therefore, a stable transfer of solutions for SPS can be achieved through tuning the wettability and topography of the substrate,[58] surface tension and viscosity of solutions, and printing speed. High viscosity is required to minimize solution flow on the substrate, which favors flow control in microgravity.[59] However, the chances of nozzle (or mask) blockage easily increase.[30] Low-viscosity solutions, which possess a high degree of flowability, can increase the difficulty of liquid control in microgravity (Figure 4e),[60] because the capillary effect dominates the liquid behavior under microgravity conditions; thus, low-viscosity solutions can easily flow along the wetting surface spontaneously without the constraint of gravity,[61,62] which can be overcome by introducing the patterned wetting substrate and structured surface,[63,64] as shown in Figure 4f. Therefore, the control of the solution transfer can be achieved in microgravity by tuning different factors related to the characteristics of the SP approaches.

### 3.1.2. Solidification of Solutions

After solution is transferred onto the substrate, it usually needs to be solidified through solvent drying. There exist complex interactions of heat and mass transport processes covered by gravity for solution solidification on the Earth.[65] Considering the droplet-based printing as an example, it will always form a nonuniform and ring-like pattern after droplet drying on a solid surface (the well-known "coffee-ring" effect),[66] which harms the quality and performance of the printed structures. Although multiple physical effects in a drying droplet, including the outward capillary flow,[66] Marangoni flow,[67] density-driven flow,[68] and gravitational sedimentation,[69] have been extensively studied to suppress the "coffee-ring" effect, the complex physical processes on the Earth are still not fully understood.[70,71] In a microgravity environment, the relative effect of Marangoni flow is strengthened because of highly reduced density-driven flows, and sedimentation of the solutes diminishes; therefore, the complex mechanical environment in drying droplets is greatly simplified, which is beneficial to experimentally investigate the evolution of the convection flow and solute transport in evaporative solidification processes.[72] The microgravity experiments will undoubtedly help to illuminate the multiphysical effects in the SPS.

Understanding the microgravity effect on the flow and phase transitions during the solidification of solutions can help to control the morphology of the printed films, which will further promote fabricating high-quality printed electronics in space. Recent focus has therefore been on the influences of gravity on the structure and performance of printed electronics.[73] For example, space experiments indicated that the inclusion of defective particles in films cannot be eliminated for complex convections under normal gravity; however, the reduced-convection environment of microgravity is conducive to preparing high-quality films with minimal defects, suggesting that growth in a convection-free environment is more favorable for achieving ordered microstructures in the films,[74] which has been further demonstrated in synthesizing homogeneous and large thin films with well-controlled crystalline orientation under simulated microgravity recently.[75]

### 3.2. Extravehicular Vacuum

The extravehicular vacuum environment has a significant effect on printing processes of solution transfer and liquid solidification. Flash evaporation may occur for many volatile liquids during the solution transfer process,[76] which can lead to material loss and even freezing, so it should be avoided. However, flash evaporation of the solvent can be beneficial to the liquid solidification process due to the disappearance of air convection and decrease in substances in a vacuum environment, which help to form the high-quality film and high-performance device. For example, the vacuum flash-assisted solution-processing method has been proved to be beneficial for the formation of large-area and high-quality perovskite films.[77] In addition, the accelerated evaporative solidification under flash evaporation can significantly improve the printing efficiency. Therefore, the vacuum drying process in space can be used as a favorable way for efficient printing of high-quality films.[78]

### 3.3. Extreme Temperature Fluctuations

The extreme temperature fluctuations have more challenges than opportunities for extravehicular printing in space. High temperature can cause thermal evaporation during the transfer of solutions, which will make the solution completely dry before its deposition; however, the thermal evaporation effect will increase the efficiency of the liquid solidification and annealing process. Thermal convection is another phenomenon caused by high temperature,[79] which can promote the mixing of solutions during printing, but the convection can easily harm the quality of the printed films and is always hard to control. For low temperatures, it is not good for the whole printing process because of the potential liquid freezing. To sum up, advantages of the high temperature can sometimes be applied for fast solidification and uniform mixing of solutions, while extreme temperature fluctuations especially low temperature should be suppressed during printing in most cases.

## 4. Potential Space Applications

A very wide range of potential space applications will emerge in the future for the SPS. Consider the potential demand for continuous renewable energy, health monitoring, and information transfer in future space missions, in this section, we will give an overview of these applications from the following three aspects: printed flexible solar cells, printed soft and wearable sensors, and printed space-based antennas.

### 4.1. Printed Flexible Solar Cell

Since the first launch of a solar-powered satellite in 1959,[80] most satellites, space stations, and rovers have used solar cells as their main power source. **Figure 5**a shows the solar arrays on the ISS. Figure 5b shows the solar-powered Zhurong Rover of China unfurling its solar panels when it reached Mars in 2021.[81] Although conventional crystalline silicon and gallium arsenide solar cells have higher efficiency, the rigidity and brittleness of these materials make it difficult for large solar panels to be freely folded and curled. In addition, the complex manufacturing processes of these solar cells on Earth have difficulty in expanding to space. Organic and perovskite photovoltaic cells not only have unique properties such as high specific power, tunable absorption window, flexibility, and foldability but also have simple printing processes that can be easily applied in space. Furthermore, the solution processability of materials allows for the possibility of large-scale production of printable solar cells using R2R printing techniques. Therefore, the printed solar cell was regarded to have the potential to become a disruptive technology for photovoltaic energy generation in space applications.[82] Recently, Reb et al. reported the launch of a suborbital rocket flight to test the performance of both perovskite and organic solar cells (POSC). The voltage–current characteristics of POSCs with different architectures were measured during flight, which indicated that the POSC showed considerably efficient performance and produced power under strong solar irradiation in a space environment. This proves the feasibility of POSC in the application of energy generation in space (Figure 5d).[83]

There are still considerable challenges for printing solar cells directly in space. The primary challenge is to develop printing processes suitable for microgravity environments. Recent experimental research of fabricating thin films for organic solar cells by the dip-coating approach was carried out under the

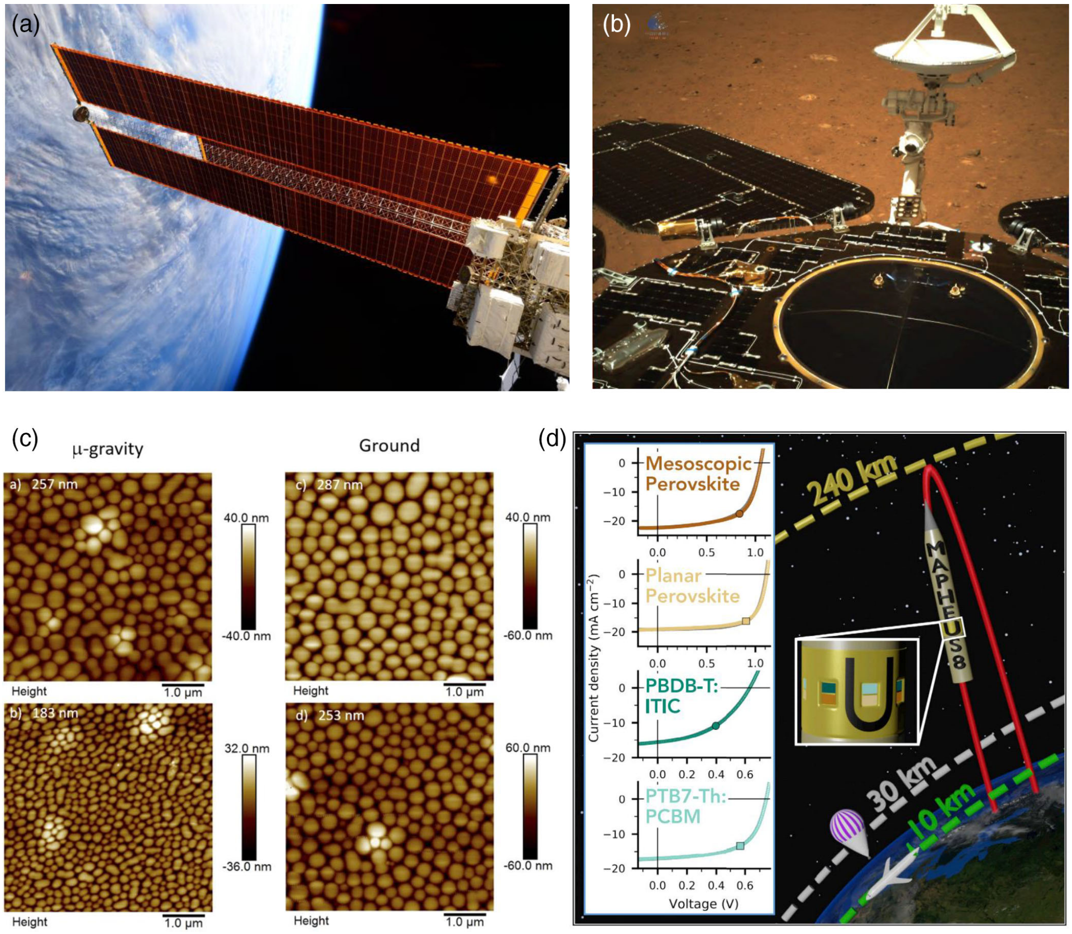



**Figure 5.** a) Solar arrays on the ISS. Image courtesy of NASA.[115] b) Solar-powered Zhurong Rover on Mars. Image courtesy of CNSA.[116] c) The surface morphology of dip-coated blend films related to organic solar cells under microgravity (left) and normal gravity (right); the prepared films have similar quality but with a difference in domain size. Reproduced with permission.[84] Copyright 2021, American Institute of Physics. d) Microgravity experiments of perovskite and organic solar cells of different architectures on a suborbital rocket flight. Reproduced with permission.[83] Copyright 2020, Elsevier.

microgravity conditions of parabolic flight. The results suggest that the dry films are of the same quality compared with the films prepared on the ground, but it has a different domain size which is related to a slowed-down phase-separation process under microgravity conditions (Figure 5c).[84] These microgravity experiments showed the possibility of transferring the production process of organic solar cells from Earth to space. Another challenge is the adaptability and stability of printed solar cells exposed to space extreme environments; therefore, the printed solar cells should be shielded from radiation to avoid degradation of their performance. Additional environmental factors in space including thermal cycling for printed solar cells should also be considered.

### 4.2. Printed Soft and Wearable Sensors

Future space explorations require a bulk of low-cost, lightweight, easy-to-make sensors to realize the Internet of Things (IOT) and human–machine interfaces in space. Printed soft and wearable sensors, with features of high stretchability, being inexpensive, and rapid mass production,[85] are anticipated to play a significant role in space applications,[86] such as space environment monitoring, astronauts' health monitoring, smart spacesuits, structural health monitoring, and space robots, as shown in **Figure 6**. When combined with printing technology, soft and wearable sensors can easily be made in space. Here, we give a brief description of the printable biochemical sensors, strain sensors, pressure sensors, and gas/vapor sensors and their possible application scenarios in space.

#### 4.2.1. Biochemical Sensors

To deal with a series of adverse effects caused by the microgravity environment on the human body, such as redistribution of body fluids, atrophy of muscles, and demineralization of bones, the physical health of astronauts needs real-time monitoring.[87] Biochemical sensors can be used for selective detection of targets such as ions and molecules in biological fluids, which provides

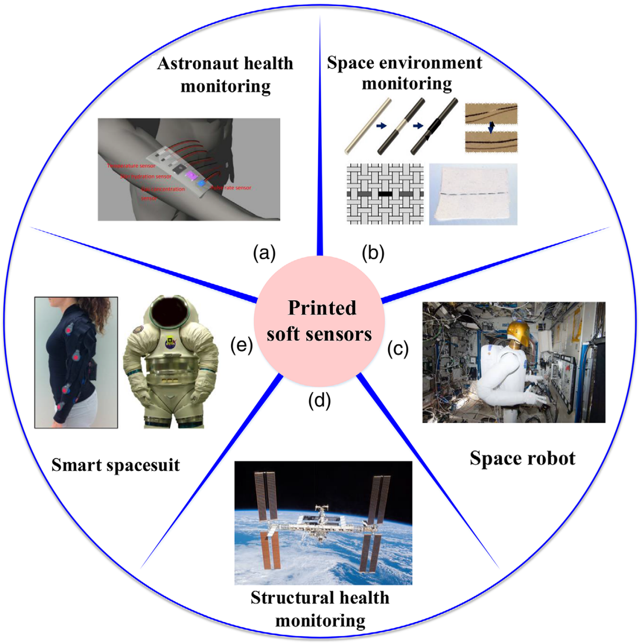



**Figure 6.** Printed wearable sensors and their applications: a) health monitoring of astronauts;b) space environment monitoring; c) the interface of the space robot; d) structure health monitoring; and e) smart spacesuit. a)–d) Image courtesy of NASA.[117–119] Reproduced with permission.[93] Copyright 2015, Elsevier.

the capability to monitor the physiological parameters of astronauts during spaceflight (Figure 6a). For example, Abellán-Llobregat et al. developed an all-printable, flexible, and noninvasive biosensor for the continuous monitoring of glucose levels in physiological fluids of humans.[88]

#### *4.2.2. Strain Sensors*

Strain sensors can measure the breathing rate, heartbeat, and pulse wave for applications in wearable systems; thus, they can be used for monitoring the astronauts' motion (Figure 6a) and connecting human–machine interfaces (Figure 6c). For instance, Tian et al. fabricated printed strain sensors with tunable working strain ranges and sensitivities based on silver nanodendrite thin films formed from screen printing. A smart glove based on the strain sensor was developed and used for monitoring human motion and gesture actions.[89] These printed strain sensors can be integrated to make convenient and intelligent systems, which provide the opportunity for continuous monitoring of the health and motion of astronauts in extreme environments.[86]

#### *4.2.3. Pressure Sensors*

Pressure sensors have attracted considerable attention in various fields, such as electronic skin,[90] soft robotics,[91] and touch screens.[92] When crews perform extravehicular activities, they must wear gas-pressurized spacesuits for a long operating time, which easily result in physical discomfort and fatigue under the human–suit interactions. Soft pressure sensors integrated inside the spacesuit can help detect human–suit interactions and guide astronauts to work safely. Anderson et al. developed a wearable pressure-sensing system to quantitatively measure the impact pressure of the spacesuit on the body's surface during dynamic extravehicular movement (Figure 6e).[93,94]

#### *4.2.4. Gas/Vapor Sensors*

Printed gas and vapor sensors are essential to continuously monitor the air quality in the inboard space stations, and they can also be used for detecting the environmental conditions of the outer planets in future exploration (Figure 6b). These compact and lightweight printed sensors can become a viable substitute for the bulky instruments currently used in space stations.[95] NASA has already developed printed gas sensors for monitoring carbon dioxide and ammonia to prevent noxious gas leakage and protect crews' health.[96]

### 4.3. Printed Space-Based Antennas

There exists asset tracking problem aboard the ISS, because all supplies must be packaged and fixed due to the weightless conditions; therefore, it is a challenge to find the needed supplies hidden inside the flight bags, as shown in **Figure** 7c,d.[97] RFID tag is a kind of noncontact automatic identification technology that can identify the target and achieve noncontact two-way communication. The RFID antenna has the advantages of noncontact reading, a wide identification range, and high positioning accuracy. Therefore, RFID antennas were previously installed around the hatchways of the space station to track the hardware.[98] RFID tags have greatly improved the operational efficiency of the ISS by tracking supplies more quickly. Compared with conventional antennas that are rarely conformal and flexible due to constraints of materials and processes, printing opens up an efficient and cost-effective way for fabricating RFID antennas, as shown in Figure 7a,b.[99] Ge et al. demonstrated a fully functional printed RFID.[100] The printed RFID tags offer an acceptable solution to asset management and the IOT for future manned space flight and planetary exploration. In addition, in the manufacturing of extra-large aperture antenna, in addition to building skeletons using space 3D printing robots (Figure 7e),[101] we can also fabricate a large area of the film antennas relying on the skeletons using large-scale R2R printing techniques in space.

## 5. Survivability for Printed Electronics in Space

The printed electronics will be exposed to outer space in use and experience harsh environments (intense radiation, high vacuum, and extreme temperatures) after printing, which pose a challenge to its normal operation. Device damage may occur, so advance protection and follow-up maintenance are required.

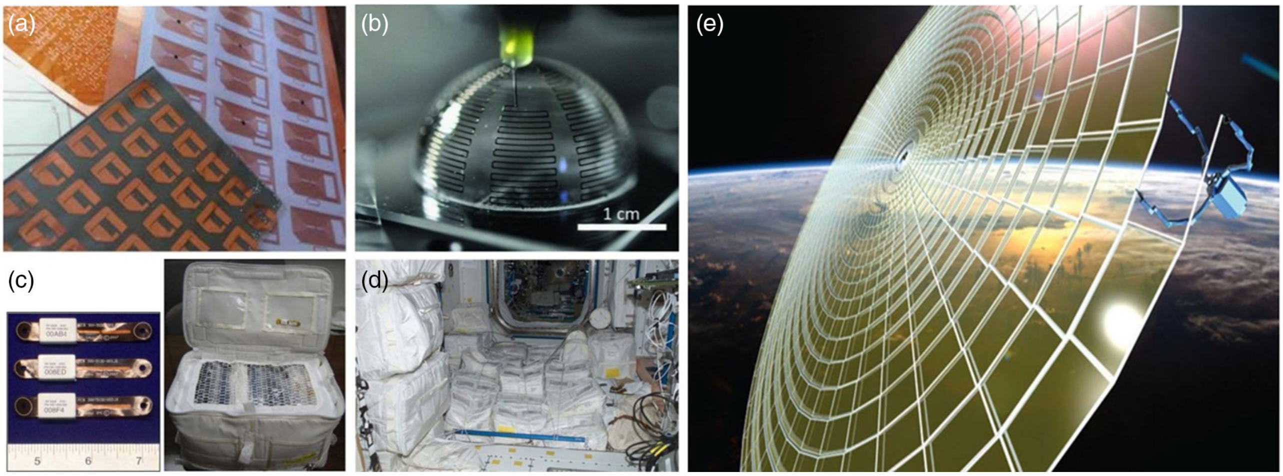



Figure 7. a)Typical microstrip-printed antenna. Image courtesy of NASA.[22] b) Direct ink printing of antenna on a curved substrate.Reproduced with permission.[120] Copyright 2011, Wiley-VCH. c) Flexible RFID tags and bags with tagged items. d) Packages of supplies on the ISS. c,d) Reproduced with permission.[97] Copyright 2007, IEEE. e) Schematic of a robot fabricating an antenna in space. Image courtesy of NASA.[101]

### 5.1. Survival and Damage in Extreme Environment

The harsh environment including radiation and thermal cycling always has a negative effect on the structure and performance of the exposed materials in space.[102] The effect of atomic oxygen erosion is the primary cause of material degradation, which can lead to a decrease in mechanical, optical, and electrical properties for printed electronics. Ouchen et al. studied the effects of atmosphere in a low Earth orbit, particularly atomic oxygen, on printed metal traces through direct exposure for 6 months aboard the ISS; they found that the atomic oxygen harmed the unpassivated printed materials, as shown in **Figure 8**a.[103] Extreme thermal cycling in space can give rise to the nonuniform stress distribution in the materials and accelerate the chemical reaction process to lead to material failure, which would accelerate the failure of printed structures. Cardinaletti et al. considered that the photovoltaic performance of the perovskites can be decimated upon phase-transition temperature, which will destroy device performances, as shown in Figure 8b.[82] Therefore, the temperature gradient and temperature cycling of printed electronics and sensors should be carefully explored and considered.

### 5.2. Encapsulation and Protection for the Printed Electronics

To prevent degradation and failure of the printed electronics exposed in an extreme environment in space, an encapsulation must be applied to achieve long-term stability and reliability of the printed devices. A flexible encapsulation can be achieved in the way of barrier foil lamination, thin-film encapsulation,

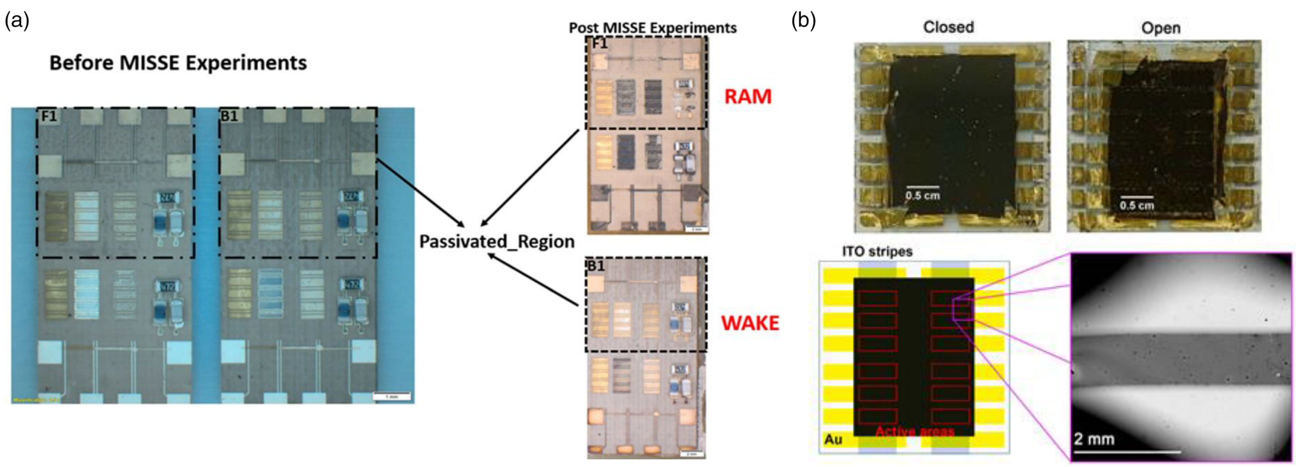



Figure 8. a) Comparison of the influences of atomic oxygen and low Earth orbit on both bare and passivated structures of printed metal traces before and after space exposure. Reproduced with permission.[103] Copyright 2012, IOP Publishing. b) Top: Macromorphological degradation of active layer films of a perovskite device with the closed (left) and open encapsulation, the open one failed during flight. Bottom: Schematic of the layout of the perovskite cells, and the right scanning electron microscope (SEM) image shows the formation of a large number of defects on the films. Reproduced with permission.[82] Copyright 2018, Elsevier.

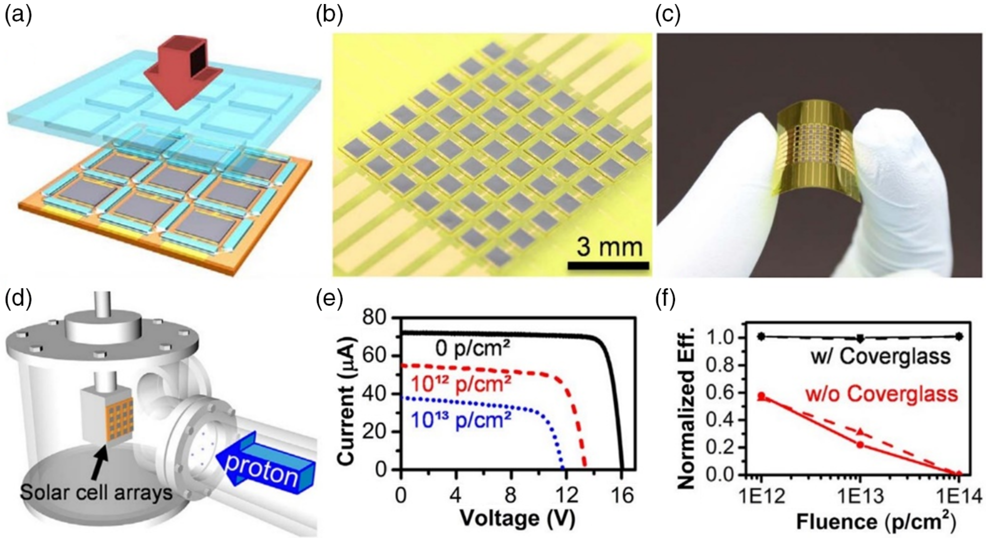



**Figure 9.** a–c) Flexible space solar cell arrays through guided printing of cover glasses. d) The solar cell arrays with and without the cover glass were exposed under protons. e) Decrease in the current–voltage characteristics of the solar cell without cover glass with the increase in irradiation fluence. f) Electrical performances of the solar cell arrays with (black lines) and without (red lines) the integrated cover glass to irradiation fluence. a-f) Reproduced with permission.[105] Copyright 2017, Elsevier.

or solution-processed encapsulation. The latter approach has a chance to be combined with the printing process to realize the integration of manufacturing and encapsulation,[104] which provides a viable way for protection of the exposed electronics made by SPS. For example, to avoid the degradation in electrical performances of the flexible solar cells, Kwak et al.[105] integrate cover glasses over the solar cell arrays through a guided-printing method, which can achieve both flexibility and radiation shielding (**Figure 9**a–c). Vacuum irradiation experiments show that the solar cells without cover glass protection can be seriously damaged by radiation, while the solar cells with cover glass show no degradation in electrical performance after irradiation (Figure 9d–f).

### 5.3. In Situ Printing for the Maintenance of Printed Electronics

The failures of electronics and devices on the spacecraft could occur at any time, especially for those exposed to the extreme environment. According to NASA's estimation, the current expenses for uploading spare electronic components are huge for maintenance and updates of spacecraft. For example, the Hubble Space Telescope was repaired and upgraded five times from 1990 to 2010, and it costs billions of dollars only at the last time. **Figure 10**a shows specialists of the Hubble mission, Michael Good and Mike Massimino, who performed maintenance tasks outside the capsule.[106] SPS techniques can be a more fast, simple, and economical approach for the in-orbit

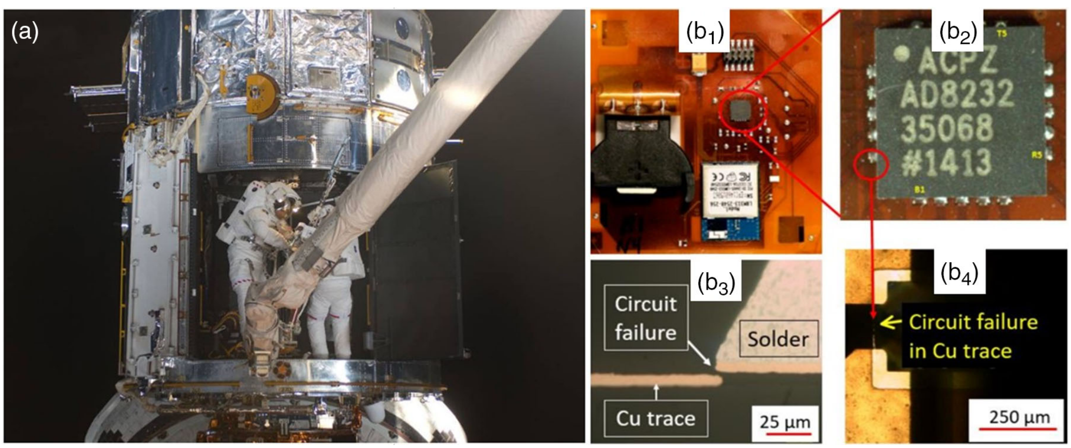



**Figure 10.** a) The astronauts perform extravehicular maintenance and upgrade missions of the Hubble Space Telescope. Image courtesy of NASA.[106] b) Reliability issues of human performance-monitoring sensor using flexible printed Au electrodes. b1–b2) Appearance of the sensor. b3–b4) Circuit failures and cracks in the copper trace. Reproduced with permission.[107] Copyright 2019, IEEE.

maintenance of failed components. A simple example is that circuit failure in copper traces such as cracks can be repaired directly by printing conductive inks onto defects (Figure 10b).[107] It is worth mentioning that those printed structures and devices can be further repaired by the SP technique. As a result, SPS can be considered as a nonsubstitutable capability for space maintenance to cope with possible failures of electronics for long-duration space missions.

## 6. Outlook

With the advancement of the manned spaceflight and deep space exploration, direct printing in space is increasingly considered as a feasible way for the sufficient and timely supply of electronics and sensors in long duration and endurance flight missions. The SP techniques, which have a long history, several advantages, and wide applications on the Earth, are now attracting more attention in the field of space manufacturing. Although many SP techniques are mature on the ground, these printing processes cannot be easily expanded into space. The applicability of the SP to space-extreme environments (including inks, substrates, printing processes, and printed structures) is the major existing problem that needs verification.

Space scientific experiments (especially microgravity and environmental exposure experiments) are essential for testing the feasibility of SPS. The microgravity effects on the transfer and solidification of solutions during printing should be considered because the involved flow and phase transition are gravity sensitive. In addition, the effects of harsh environments (such as radiation) on printed structures should be evaluated. Microgravity conditions may be conducive to the formation of large-area and high-quality materials; therefore, devices and sensors with superior performance can be printed in space and then returned to the Earth, helping to create commercial activity in low Earth orbit by promoting space printing of high-value industrial products for use on Earth.

With advantages of softness, handiness, and low cost, the SPS of electronics will have a disruptive impact on space applications, such as large-area and flexible solar cells, intelligent wearable systems for astronauts' health monitoring, soft electronics for monitoring plant physiological information, large-scale thin-film antennas, and timely in situ repair in orbit. Richer application scenarios can be imagined and exploited in the future, and the development of the SPS should be led by these applications in space. Undoubtedly, SPS techniques provide infinite possibilities for the construction of space-smart infrastructure.

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## Conflict of Interest

The authors declare no conflict of interest.

## Keywords

flexible printed electronics, microgravity, solution printing, space manufacturing, 3D printing

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