Ultra-Portable Solar-Powered 3D Printers for Onsite Manufacturing of Medical Resources

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INTRODUCTION: The first space-based fused deposition modeling (FDM) 3D printer is powered by solar photovoltaics. This study seeks to demonstrate the feasibility of using solar energy to power a FDM 3D printer to manufacture medical resources at the Mars Desert Research Station and to design an ultra-portable solar-powered 3D printer for off-grid environments.

METHODS: Six solar panels in a 3 $\times$ 2 configuration, a voltage regulator/capacitor improvised from a power adapter, and two 12V batteries in series were connected to power a FDM 3D printer. Three designs were printed onsite and evaluated by experts post analogue mission. A solar-powered 3D printer composed of off-the-shelf components was designed to be transported in airline carry-on luggage.

RESULTS: During the analogue mission, the solar-powered printer could only be operated for $<$ 1 h/d, but was able to fabricate a functional dental tool, scalpel handle, and customized mallet splint over 2 d. Post analogue mission, an ultra-portable plug-and-play solar-powered 3D printer was designed that could print an estimated 16 dental tools or 8 mallet finger splints or 7 scalpel handles on one fully charged 12V 150Wh battery with a 110V AC converter.

CONCLUSION: It is feasible to use solar energy to power a 3D printer to manufacture functional and personalized medical resources at a Mars analogue research station. Based on these findings, a solar-powered suitcase 3D printing system containing solar panels, 12V battery with charge controller and AC inverter, and back-up solar charge controller and inverter was designed for transport to and use in off-grid communities.

KEYWORDS: photovoltaics, digital fabrication, additive manufacturing, space medicine, long-duration space missions, global health.

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Fused deposition modeling (FDM) 3D printing is an additive manufacturing process that builds objects of various geometries, layer by layer, from thermoplastic materials.[16] The primary advantage of 3D printing technology for long-duration space missions is onsite manufacturing of resources on demand. In 2014, the first space-based FDM 3D printer explored whether functional objects, replacement parts, and customized tools could be 3D printed with ABS thermoplastic on the International Space Station.[8] FDM 3D printing technology was evaluated for the fabrication of different rover wheel tread, wind turbine, and vehicle replacement part designs at a Mars analogue research station in 2013.[11] The suitability of 3D printing surgical instruments for long-duration space missions was recently evaluated.[16]

A human mission on the surface of Mars will require electrical power from in situ renewable resources.[3] Solar photovoltaics (PV), which convert sunlight into electricity, have been shown to be a technically viable, environmentally friendly, and socially acceptable technology to power long-duration robotic and human missions in space.[13,17] A 2014 study reviewed several solar-powered 3D printer designs and demonstrated the technical feasibility of powering two different mobile, open-source 3D printing systems with solar PV for potential use in off-grid rural communities.[7] Solar powered 3D printers could provide onsite manufacturing capabilities and potentially transform local economies for the 1.4 billion people who lack access to electricity.[5–7]

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This study seeks to demonstrate the technical feasibility of powering a FDM 3D printer using solar energy to manufacture functional and customized medical resources at a Mars analogue research station. This study describes a 3D printer with a PV system improvised on site at a remote Mars analogue research station by providing a detailed components summary. This technology demonstration was assessed by recording observations and evaluating three case study prints appropriate for providing medical care on a Mars mission. Post analogue mission, the findings from this work were used to design an ultra-portable, plug-and-play solar-powered 3D printing system suitable for transport to and use in remote, off-grid communities.

METHODS

The Cube® 2nd generation 3D printer (3D Systems Corp., Rock Hill, SC) was selected for: 1) its portability because of its small size and low weight, which permitted its transport inside airline carry-on luggage; and 2) its single thermoplastic extruder, a feature shared with the first space-based 3D printer (Made in Space Inc., Mountainview, CA). The recommended operating room temperature for this printer is 16–29°C (60–85°F).[12] The print layer resolution is 250 microns. The maximum print object size is 14 cm × 14 cm × 14 cm (5.5″ by 5.5″ by 5.5″). Before the analogue mission, the power usage for a test print of a mallet splint was measured using a multimeter to ensure that the printing process would not exceed the Mars analogue research station power limitations.

The Cube® 2nd generation 3D printer's electrical outlet requirements are 100–240 V at 50/60 Hz.[12] The published maximum power requirements of this printer are 24V DC and 3.75 A. The printer's 120V AC power supply can be bypassed and the printer can be run from 24V DC. **Fig. 1** shows how a PV-based power source was created on site in 2014 during an analogue mission at the Mars Desert Research Station (Hanksville, UT) with available materials to deliver this required power.[9] The solar array consisted of six modular solar panels (Robots Everywhere, San Mateo, CA) in a 3 × 2 configuration, with each pair of panels connected in parallel and the three pairs of panels wired in series to achieve a nominal output of 27V. Two 12V sealed lead acid batteries were connected in series for a 24V nominal output. An insulation-piercing connection was made between the pair of wires from the solar panel array and the output side (DC side) of the printer's power adapter, which acted as a filter capacitor and provided voltage regulation. This circuit was plugged into the printer. While the printer was operated inside the greenhouse as per mission simulation stipulations, the solar panels were placed outside the greenhouse on the ground.

The three pre-existing digital designs (mallet splint, dental tool, and scalpel handle) shown in **Fig. 2** were chosen for testing because they are valuable and relevant medical resources for a long-duration space mission.[4,10,16] The digital files in .STL format were converted to .CUBE format with Cube® 2.0.1 printing software installed on a 2009 MacBook laptop (Apple Inc., Cupertino, CA) running on OSX Yosemite version 10.10.2. The digital files were transferred to the printer using a portable USB memory stick. For the dental tool and mallet splint design, the printer was run at the following settings; print mode at "strong," raft at "off," supports at "off," and model in inches at "no." To avoid warping of the scalpel handle during the printing process, the printer's settings were changed to: raft at "on." To help maintain adherence of the printed object to the glass platform during the FDM printing process, two materials were used, depending on the length of the object. Scotch-Blue™ Painter's Tape #2090 (3M, St. Paul, MN) was applied to the printing platform for the finger splint. 3D Systems Cube-Stick™ glue was used for printing the dental tool and scalpel handle designs because they were longer objects compared to the finger splint. The printer was operated inside the greenhouse to avoid off-gassing in the simulated closed loop environment of the Mars analogue crew living quarters. Prior to printer use, the greenhouse ambient temperature was checked to ensure it was within the printer's operating temperature range.[12]

The Cube® 2nd generation 3D printer uses FDM technology, which feeds an ABS thermoplastic filament into an extruder which heats up to 280°C (536°F) and deposits the semiliquid thermoplastic in a digitally

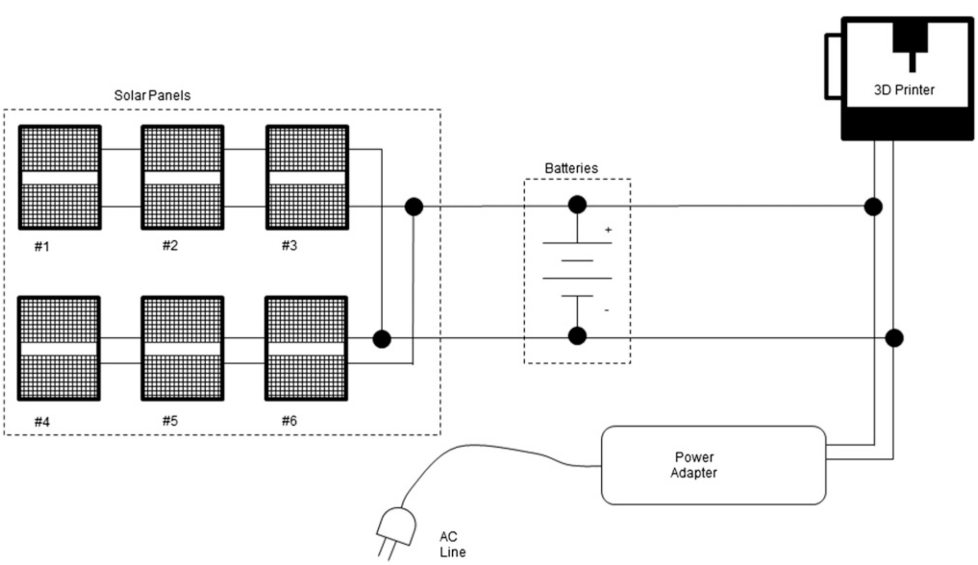

Fig. 1. Six 9V solar panels deliver 27V into an improvised voltage regulator that outputs a constant 24V to charge two lead-acid 12V batteries (5Ah, 18Ah) in series which provide the energy storage necessary to deliver the required current to operate the FDM 3D printer for less than 1 h/d.

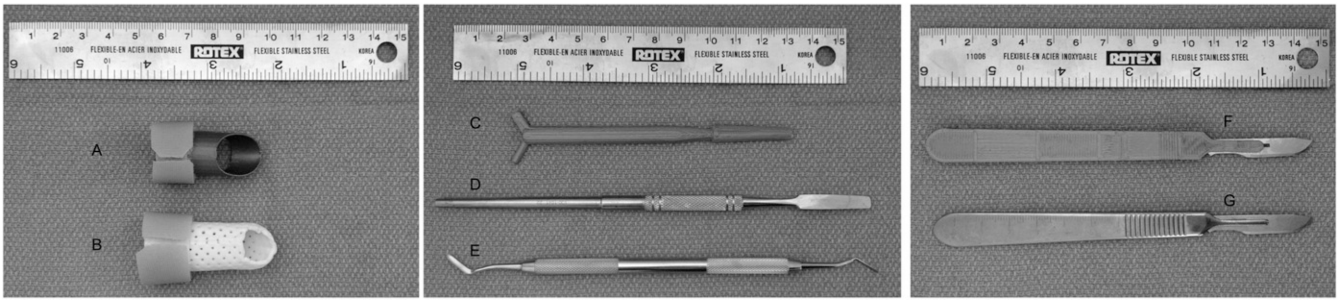

Fig. 2. Left panel: A) 3D printed ABS thermoplastic custom mallet finger splint, and B) handmade thermoplastic custom mallet finger splint. Middle panel: C) 3D printed ABS thermoplastic dental filling replacement tool, D) conventional stainless steel dental spatula, and E) conventional stainless steel dental plastic filling instrument. Right panel: F) 3D printed ABS thermoplastic scalpel handle with #10 blade, and G) conventional stainless steel scalpel handle with #10 blade.

controlled fashion.[12] The print platform shifts down vertically to permit more horizontal layers to be added until the entire 3D shape of the printed object has been fabricated.

The print time was displayed on the touchscreen interface of the printer and was recorded at the conclusion of each print. The mallet splint was removed from the print bed manually and a 1.5 cm wide by 6.5 cm long circumferential hook and loop strap was affixed to the proximal end. The two print platforms containing the dental tool and scalpel handle were placed in a container of tap water with a small amount (< 5 ml) of liquid dishwasher detergent to facilitate removal of the prints that were affixed to the platform with glue. Each glass print platform was rinsed with tap water and dried before reuse. The raft material was removed from the scalpel handle using a Xcelite® 170M wire cutter shear (Apex Tool Group, Sparks, MD) while protective eyewear was worn.

The functional performance of the three case study prints was evaluated post analogue mission by independent assessors using prior research protocols.[15,16] A hand therapist assessed the function of the customized mallet splint by checking splint fit and recording the range of motion of the proximal interphalangeal joint with a goniometer when the splint was worn by a subject (Wong JY. Personal communication, 2014). A dentist evaluated the functionality of the printed dental tool by completing a simulated filling replacement task with CAVIT™ paste (3M ESPE, St. Paul, MN) on a plaster dental mold.[15] A surgeon tested the performance of the scalpel handle by using the #10 blade inserted on the scalpel handle to make a 5-cm full-thickness skin incision on a chicken sample.[16]

Post analogue mission, an Internet search was conducted to identify plug-and-play portable solar panels, batteries, and inverters that could meet the printer's power needs for fabricating the three case study prints and that could be easily transported in airline carry-on luggage for safer handling of delicate components and to minimize baggage fees. The goal was to create a plug-and-play suitcase PV powered 3D printer so physicians visiting a remote community can carry this printer with them to fabricate necessary medical resources on site. A portable 30W Escape 30 solar panel briefcase and Yeti 150 14 amp-hour (Ah) battery with a charge controller and 110V AC inverter (Goal Zero LLC, Bluffdale, UT) were purchased online to create an ultra-portable plug-and-play PV powered 3D printer (**Fig. 3**). A single test print of a custom mallet splint was conducted on a fully charged lead acid battery.

The energy usage in Watt-hours (Wh) for each test print was calculated by using a multimeter to measure the current draw from a 13.9V power supply into a 120V inverter, which then powered the 3D printer (**Table I**). The number of prints that could be fabricated on one fully charged battery was calculated by dividing the Wh rating of the battery by the energy usage required for each test print.

Although the Yeti 150 battery with a charge controller and 110V AC inverter is deemed safe for air travel according to its manufacturer, airline-specific requirements are subject to change without notice and may prohibit the transportation of this device (Goal Zero. Personal communication, 2015). Thus, the ultra-portable PV-powered 3D printing system includes a back-up solar charge controller and inverter in case the lead acid battery needs to be obtained locally. A Model SBC-6112 solar PV charge controller (PowerStream Technology, Urem, UT), a NEXXTech 115V inverter (Orbyx Electronics, Concord, Ontario, Canada), and a used 12V lead acid battery were obtained. An alternate PV power configuration for the Cube® 2nd generation 3D printer was assembled with the Escape 30 solar panel briefcase (Fig. 3). This configuration was tested by observing whether the charging indicator of the charge controller showed that the Escape 30 solar panel briefcase was charging the used lead acid battery.

RESULTS

The design schematics of the PV system improvised and tested on site during the Mars analogue mission are displayed in Fig. 1. Care was required to prevent dust coverage of the panels. The solar panels had to be moved by a crewmember over the course of the day to avoid shadows from blocking the panels' access to sunlight. The lightweight solar panels were not secured and, thus, were not suitable for use during high wind conditions. The insulation-piercing connection made in the printer's power adapter voided the printer manufacturer's warranty. The printer did not automatically shut off after a print was completed, so the printing process had to be monitored in order to avoid

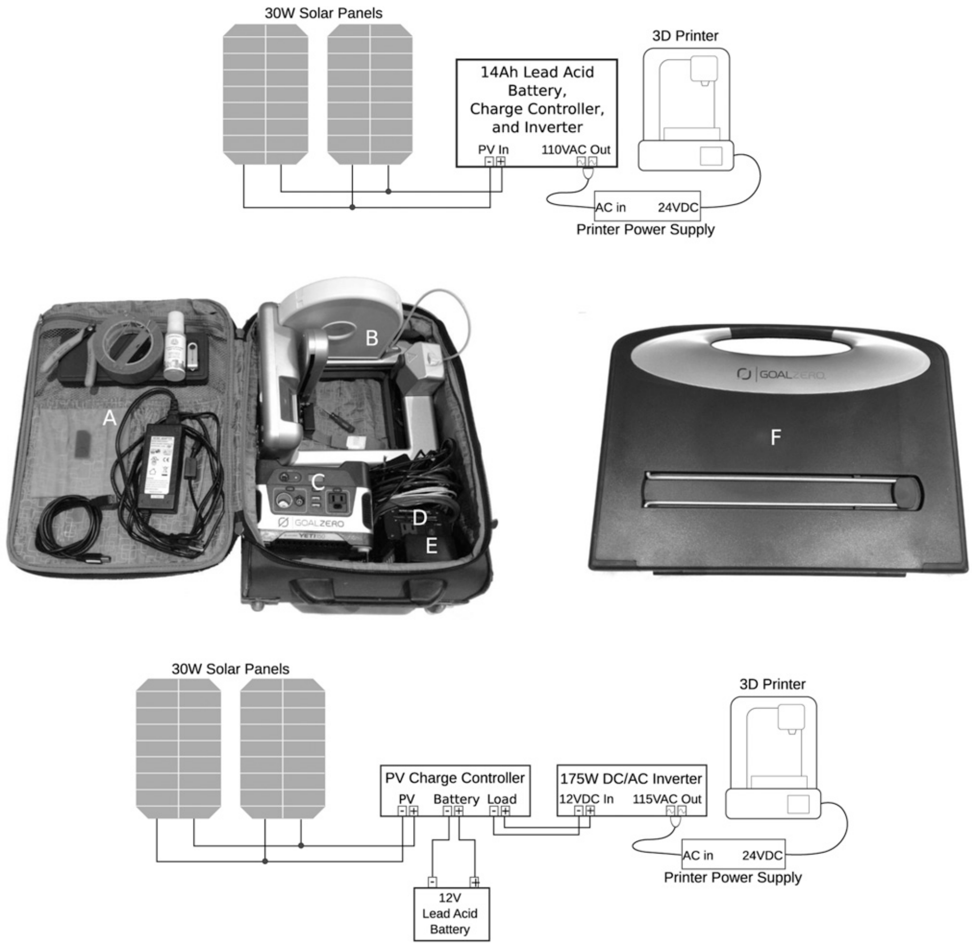

Fig. 3. Top panel: A schematic of the ultra-portable plug-and-play PV-powered 3D printer with solar panels and battery with inverter and charge controller. Middle panel: The PV-powered 3D printer system components are shown packed inside a carry-on (52.5 cm long × 36.5 cm wide × 23.5 cm thick) suitcase. A) Printer accessories, B) FDM 3D printer (4.3 kg) with ABS thermoplastic printer cartridge (0.64 kg), C) battery with inverter and charge controller (5.4 kg), D) back-up inverter (0.61 kg), E) back-up PV charge controller (0.44 kg), and F) 53.5 cm × 5 cm × 40.6 cm portable solar panels (5.4 kg) shown folded. Bottom panel: A schematic of an alternative set-up of the PV-powered suitcase 3D printer with portable solar panels, a locally obtained lead acid battery, and back-up PV charge controller and inverter.

unnecessary drainage of power. No noxious odors or fumes were reported by the mission crew.

The printer could be operated for less than 1 h/d during the month of December at the remote Mars analogue research station located at 38°24′23.25″ N and 110°47″30.85″ W. The system successfully printed the three functional medical designs over 2 d during the Mars analogue mission (Fig. 2). The mallet splint was successfully printed on the first day, but a second test print was aborted due to inadequate power. The dental tool and scalpel handle were printed on the second day.

The printed custom mallet splint fit securely and comfortably while permitting full range of motion (0–102°) of the proximal interphalangeal joint and maintaining the distal interphalangeal joint in full extension. Both simulated incising and temporary dental filling replacement tasks were successfully completed by healthcare professionals using the 3D printed scalpel handle and dental tool, respectively.

Fig. 3 shows an ultra-portable, plug-and-play PV-powered 3D printing system composed of off-the-shelf components that was created for transport to and use in off-grid communities. The 3D printer with printer cartridge, portable 12V battery with 110V AC inverter, solar PV charge controller, inverter, and printer accessories can fit inside a single carry-on suitcase. The portable solar panel briefcase is within the maximum size limits for carry-on baggage for most airlines.[2] This printer can also be operated using electric grid power. The portable 12V battery, which takes between 11 to 22 h to fully charge, was rated at 150 Wh. The fully charged battery could print an estimated 16 dental tools or 8 mallet finger splints or 7 scalpel handles. A functional custom mallet splint was printed using this fully charged battery and was evaluated by a hand therapist.

Fig. 3 also shows an alternate PV power set-up if a lead acid battery cannot be transported onboard an aircraft and a used lead acid battery is obtained locally. The solar charge controller showed that the solar panels are capable of charging a used lead acid battery at a voltage greater than 12.6V during the month of February at a geographic location of 43.7° N and 79.4° W.

Table I. List of 3D Printed Objects, Print Times, 3D Design Software, and Energy Usage for Three Test Prints Fabricated Onsite Using PV at a Remote Mars Analogue Research Station.

PRINTED OBJECT & ITS PRINT TIME	3D DESIGN SOFTWARE	ENERGY USAGE (IN WH)
Dental tool (12 min)	AutoCAD Inventor	9.2
Mallet splint (23 min)	OpenSCAD	17.6
Scalpel handle (25 min)	Solidworks 3D	19.2

The energy usage in Wh for each test print was calculated post analogue mission by multiplying the average current draw (3.3A) × 13.9V × print time.

DISCUSSION

It was feasible to power a commercial 3D printer using PV to print functional and customized medical resources on site at a remote Mars analogue research station. However, the PV system improvised on site during the analogue mission had several drawbacks, including: 1) the use of an insulation-piercing connection of the printer power adapter which voided the manufacturer's safety warranty; and 2) its limited power, which restricted the number of objects that could be fabricated per day.

Based on these findings, the study author sought to assemble a plug-and-play PV-powered suitcase 3D printer that could meet the power needs for printing the case study prints in off-grid regions. The fully charged combined battery/inverter/charge controller could print an estimated 16 dental tools or 8 mallet finger splints or 7 scalpel handles, assuming that the battery operates at 100% efficiency. A functional custom mallet splint was successfully fabricated using the aforementioned fully charged battery. This ultra-portable PV-powered design can accommodate the use of a locally obtained lead acid battery in case it is not possible to transport the combined battery/inverter/charge controller onboard an aircraft. Future work will determine the optimal design to permit the incorporation of locally obtained solar panels for 3D printing.

There are limitations to this study's technology demonstration of PV powered 3D printing for Mars missions. The solar irradiance on Mars is 43% that of Earth.[14] The PV panels used in this study are less efficient than the International Space Station solar arrays.[17] The first space-based 3D printer uses at least 196W at 28V, which differs from the power draw of the commercial printer used in this study.[1] The power draw of a printed object will depend on fill density, printer settings, object size, and geometric complexity, with complex shapes taking longer and requiring more energy to print. Future work could involve identifying more printable designs to meet the medical needs of a Mars mission and measuring power draws when printing new test prints with a gravity independent 3D printer powered by batteries charged by the high-efficiency International Space Station solar panels exposed to Mars insolation levels.

3D printing offers the potential to upcycle plastic waste and locally produce environmentally friendly, affordable, appropriate, and customized resources on demand while leapfrogging inadequate supply and distribution chains in isolated regions.[6,7] Current portable plug-and-play solar panels, batteries, charge controllers, and inverters can address the modest power needs of FDM 3D printers. Future work will demonstrate whether this study's ultra-portable plug-and-play solar-powered 3D printer configuration can be carried by physicians who travel to remote off-grid communities and used to manufacture low-cost medical resources and other functional objects on site.

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