IPP 3D Printing Extensions (3D)

Status: Interim

Abstract: This white paper defines an extension to the Internet Printing Protocol that supports printing of physical objects by Additive Manufacturing devices such as 3D printers.

This document is a White Paper. For a definition of a "White Paper", see:

http://ftp.pwg.org/pub/pwg/general/pwg-process30.pdf

This document is available electronically at:

http://ftp.pwg.org/pub/pwg/ipp/ws/wd-sweet-ipp3d-20151116.docx

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Title: *IPP 3D Printing Extensions (3D)*

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1. Introduction

This white paper defines an extension to the Internet Printing Protocol (IPP) that supports printing of physical objects by Additive Manufacturing devices such as three-dimensional (3D) printers. The attributes and values defined in this document have been prototyped using the CUPS software [CUPS].

The primary focus of this document is on popular Fused Deposition Modeling (FDM) devices that melt and extrude ABS and/or PLA filaments in layers to produce a physical, 3D object. However, the same attributes can be used for other types of 3D printers that use different methods and materials such as Laser Sintering of powdered materials and curing of liquids using ultraviolet light.

This document also addresses common Cloud-based issues by extending the IPP Shared Infrastructure Extensions [PWG5100.18], although how such services are provisioned or managed is out of scope.

This document does not address the larger issue of choosing a common Object Definition Language (ODL) for interoperability, however there are suggested MIME media type names listed in section 7 for several formats in common use as well as strategies for mapping material definitions in the Job Ticket to the ODL content.

* 1. Previous Solutions

3D printers are commonly bundled with so-called "slicer" software that converts ODL files into a suitable low-level format (G-code, etc.) for the printer. The file produced by the slicer software is then copied to a SD memory card and inserted in a slot on the printer where it can be selected for printing. Some printers also support job submission via USB interface, and third-party Cloud solutions often use the USB interface to print jobs received through the Cloud.

Unfortunately, the USB serial protocol used for 3D printers does not support identification of 3D printers or their capabilities, nor is there a single standard protocol in use during job submission or processing (printing). This combined with the use of printer-specific file formats makes direct printing infeasible outside the narrow range of computers supported by the manufacturer, an issue that has plagued 2D printing for years and that the PWG IPP workgroup has helped to mitigate through projects such as IPP Everywhere.

1. Terminology
   1. 3D Printing Terminology

*Additive Manufacturing*: A 3D printing process where material is progressively added to produce the final output.

*Binder Jetting*: A 3D printing process that uses a liquid binder that is jetted to fuse layers of powdered materials.

*Digital Light Processing*: A 3D printing process that uses light with a negative image to selectively cure layers of a liquid material.

*Fused Deposition Modeling*: A 3D printing process that extrudes a molten material to draw layers.

*Laser Sintering*: A 3D printing process that uses a laser to melt and fuse layers of powdered materials.

*Material Jetting*: A 3D printing process that jets the actual build materials in liquid or molten state to produce layers.

*Selective Deposition Lamination*: A 3D printing process that laminates cut sheets of material.

*Stereo Lithography*: A 3D printing process that uses a laser to cure and fuse layers of liquid materials.

*Subtractive Manufacturing*: A 3D printing process where material is progressively removed to produce the final output.

* 1. Acronyms and Organizations

*CNC*: Computer Numerical Control

*DLP*: Digital Light Processing

*FDM*: Fused Deposition Modeling

*IANA*: Internet Assigned Numbers Authority, http://www.iana.org/

*IETF*: Internet Engineering Task Force, http://www.ietf.org/

*ISO*: International Organization for Standardization, <http://www.iso.org/>

*ODL*: Object Definition Language

*PWG*: Printer Working Group, http://www.pwg.org/

*SD*: SD Card Association, http://www.sdcard.org/

*SDL*: Selective Deposition Lamination

*SL*: Stereo Lithography

*USB*: Universal Serial Bus, http://www.usb.org/

1. Rationale for IPP 3D Printing Extensions

Existing specifications define the following:

1. IPP/2.0 Second Edition [PWG5100.12] defines version 2.0, 2.1, and 2.2 of the Internet Printing Protocol which defines a standard operating and data model, interface protocol, and extension mechanism to support traditional Printers;
2. IPP Everywhere [PWG5100.14] defines a profile of existing IPP specifications, standard Job Template attributes, and standard document formats;
3. IPP Shared Infrastructure Extensions (INFRA) [PWG5100.18] defines an interface for printing through shared services based in infrastructure such as Cloud servers;
4. The 3D Manufacturing Format Core Specification & Reference Guide v1.0 [3MF] defines an XML schema and file format for describing 3D objects with one or more materials.

Therefore, this IPP 3D Printing Extensions (3D) document should define IPP attributes, values, and operations needed to support printing of 3D objects, status monitoring of 3D printers and print jobs, and configuration of 3D printer characteristics and capabilities.

* 1. Use Cases
     1. Print a 3D Object

Jane is viewing a 3D object and wishes to print it. After initiating a print action, she selects a 3D printer on the network, specifies material and print settings, and submits the object for printing.

* + 1. Print a 3D Object Using Loaded Materials

Jane is viewing a 3D object and wishes to print it. After initiating a print action, she selects a 3D printer on the network that has the material(s) she wishes to use, specifies additional print settings, and submits the object for printing.

* + 1. Print a 3D Object with Multiple Materials

Jane wants to print a multi-material object on a single-material Printer. Jane uses software on her Client device to create Document data that instructs the Printer to pause printing and provide status information at specific layers so that she can change materials at the Printer and resume printing with the new material.

* + 1. View a 3D Object During Printing

Jane has submitted a 3D print Job that will take 4 hours to complete. She can visually monitor the progress of the Job through a web page provided by the Printer.

* 1. Exceptions
     1. Clogged Extruder

While printing a 3D object, the extruder becomes clogged. The printer stops printing and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Extruder Temperature Out of Range

While printing a 3D object, the extruder temperature goes out of range for the material being printed. The printer pauses printing until the temperature stabilizes and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Extruder Head Movement Issues

While printing a 3D object, the extruder head movement becomes irregular. The Printer stops printing and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Filament Feed Jam

While printing a 3D object, the filament jams and cannot be fed into the extruder. The printer stops printing and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Filament Feed Skip

While printing a 3D object, the filament extrusion rate is insufficient to maintain proper printing. The printer stops printing and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Material Empty

While printing a 3D object, the printer runs out of the printing material. The printer pauses printing until more material is loaded and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Material Adhesion Issues

While printing a 3D object, the printed object releases from the build platform or the current layer is not adhering to the previous one. The printer stops printing and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Print Bed Temperature Out of Range

While printing a 3D object, the print bed temperature goes out of the requested range. The printer pauses printing until the temperature stabilizes and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert.

* + 1. Print Bed Not Clear

When starting to print a 3D object, the Printer detects that the build platform is not empty/clear. The Printer stops printing and sets the corresponding state reason to allow Jane's Client device to discover the issue and display an appropriate alert. The Printer starts printing once the build platform is cleared.

* 1. Out of Scope

The following are considered out of scope for this document:

1. Definition of new file formats; and
2. Support for Subtractive Manufacturing technologies such as CNC milling machines.
   1. Design Requirements

The design requirements for this document are:

1. Define attributes and values to describe supported and loaded (ready) materials used for FDM; and
2. Define attributes and values to describe FDM printer capabilities and state

The design recommendations for this document are:

1. Support 3D printing technologies other than FDM

1. Technical Solutions/Approaches

Current 3D printers offer limited connectivity and status monitoring capabilities. Many printers simply read printer-ready files from SD memory cards, with all interaction and status monitoring happening at the printer's console.

Makerbot Industries uses a proprietary protocol and file format that generalizes some aspects of the interface between a host device and 3D printer. However, this solution is highly specific to FDM printing and does not offer any spooling or security functionality.

Various other proprietary protocols and interfaces are also in use, typically based on the USB serial protocol class for direct connection to a host device. And there are a number of Cloud-based solutions emerging that utilize a proxy device that communicates with the Cloud and 3D printer.

Given that the 3D printing industry and technologies are still undergoing a great deal of change and development, certain aspects of 3D printing may be difficult or infeasible to standardize. However, a stable, reliable, and secure interface between host device (IPP Client) and 3D printer (IPP Printer) can be defined today in a way that allows for future changes to be incorporated without difficulty.

* 1. High-Level Model

The IPP/1.1 Model and Semantics [RFC2911], the IETF Printer MIB [RFC3805], and the IETF Finisher MIB [RFC3806] already define a comprehensive model for the operation and data elements of a typical 2D printer. Figure 1 shows the generalized IPP model. The IPP Server provides the external network interface for IPP Clients, while the Print Service manages and processes Jobs and communicates with the Output Device(s) and their sub-units.

IPP objects in the model include Printers, Jobs, Documents, and Subscriptions. Each object has associated named attributes, each with one or more strongly typed values. Status attributes are immutable (READ-ONLY) while Description and Template attributes can be mutable (READ-WRITE). Objects can be the target of IPP operations, for example the Printer object accepts the Create-Job operation to create new Job objects for that Printer.

The IPP Printer object contains zero or more Job objects and is responsible for managing, scheduling, and processing Jobs. It also provides the current state of the Output Device(s) and communicates with them as needed.

The IPP Job object contains zero or more Document objects and tracks the progress of the Job throughout its life cycle. The Job Ticket (attributes supplied when creating the Job) and Job Receipt (attributes describing the final disposition of the Job) are also stored here.

The IPP Document object contains the document data or a reference (URI) to the data and tracks the progress of the Document throughout its life cycle. The Document Ticket (attributed supplied when creating the Document) and Document Receipt (attributes describing the final disposition of the Document) are also stored here.

The IPP Subscription object contains event notifications for one or more conditions that are being monitored. The Subscription Ticket (attribute supplied when creating the Subscription) is also stored here and determines whether notifications are pushed (email, instant messaging, etc.) or pulled (IPP Get-Notifications operation).



Figure - Generalized IPP Model (RFC 2911)

* 1. 3D Print Service

3D printing uses a variation of the traditional Print service that maintains state and capability information specific to 3D printing. Table 1 lists the operations that are used by the 3D Print service. Table 2 lists additional operations that are used by Cloud-based services. And Table 3 lists the various attributes that are used by all 3D Print services.

Table 1 - 3D Print Service Operations

| **Code** | **Operation Name** | **Reference** |
| --- | --- | --- |
| 0x0004 | Validate-Job | RFC 2911 |
| 0x0005 | Create-Job | RFC 2911 |
| 0x0006 | Send-Document | RFC 2911 |
| 0x0007 | Send-URI | RFC 2911 |
| 0x0008 | Cancel-Job | RFC 2911 |
| 0x0009 | Get-Job-Attributes | RFC 2911 |
| 0x000A | Get-Jobs | RFC 2911 |
| 0x000B | Get-Printer-Attributes | RFC 2911 |
| 0x000C | Hold-Job | RFC 2911 |
| 0x000D | Release-Job | RFC 2911 |
| 0x0010 | Pause-Printer | RFC 2911 |
| 0x0011 | Resume-Printer | RFC 2911 |
| 0x0013 | Set-Printer-Attributes | RFC 3380 |
| 0x0014 | Set-Job-Attributes | RFC 3380 |
| 0x0015 | Get-Printer-Supported-Values | RFC 3380 |
| 0x0016 | Create-Printer-Subscriptions | RFC 3995 |
| 0x0017 | Create-Job-Subscriptions | RFC 3995 |
| 0x0018 | Get-Subscription-Attributes | RFC 3995 |
| 0x0019 | Get-Subscriptions | RFC 3995 |
| 0x001A | Renew-Subscription | RFC 3995 |
| 0x001B | Cancel-Subscription | RFC 3995 |
| 0x001C | Get-Notifications | RFC 3996 |
| 0x0022 | Enable-Printer | RFC 3998 |
| 0x0023 | Disable-Printer | RFC 3998 |
| 0x0024 | Pause-Printer-After-Current-Job | RFC 3998 |
| 0x0025 | Hold-New-Jobs | RFC 3998 |
| 0x0026 | Release-Held-New-Jobs | RFC 3998 |
| 0x002D | Cancel-Current-Job | RFC 3998 |
| 0x0038 | Cancel-Jobs | PWG 5100.11 |
| 0x0039 | Cancel-My-Jobs | PWG 5100.11 |
| 0x003A | Resubmit-Job | PWG 5100.11 |
| 0x003B | Close-Job | PWG 5100.11 |
| 0x003C | Identify-Printer | PWG 5100.13 |

Table 2 - Additional Cloud-Based 3D Print Service Operations

| **Code** | **Operation Name** | **Reference** |
| --- | --- | --- |
| 0x003F | Acknowledge-Document | PWG 5100.18 |
| 0x0040 | Acknowledge-Identify-Printer | PWG 5100.18 |
| 0x0041 | Acknowledge-Job | PWG 5100.18 |
| 0x0042 | Fetch-Document | PWG 5100.18 |
| 0x0043 | Fetch-Job | PWG 5100.18 |
| 0x0044 | Get-Output-Device-Attributes | PWG 5100.18 |
| 0x0045 | Update-Active-Jobs | PWG 5100.18 |
| 0x0046 | Deregister-Output-Device | PWG 5100.18 |
| 0x0047 | Update-Document-Status | PWG 5100.18 |
| 0x0048 | Update-Job-Status | PWG 5100.18 |
| 0x0049 | Update-Output-Device-Attributes | PWG 5100.18 |

Table 3 - 3D Print Service Attributes

| **Attribute Name** | **Object** | **Reference** |
| --- | --- | --- |
| attributes-charset | All/operation | RFC 2911 |
| attributes-natural-language | All/operation | RFC 2911 |
| charset-configured | Printer | RFC 2911 |
| charset-supported | Printer | RFC 2911 |
| compression | operation | RFC 2911 |
| compression-supported | Printer | RFC 2911 |
| document-format | Document/operation | RFC 2911 |
| document-format-default | Printer | RFC 2911 |
| document-format-supported | Printer | RFC 2911 |
| document-name | Job/Document/ operation | RFC 2911 |
| generated-natural-language-supported | Printer | RFC 2911 |
| ipp-attribute-fidelity | operation | RFC 2911 |
| ipp-features-supported | Printer | PWG 5100.13 |
| ipp-versions-supported | Printer | RFC 2911 |
| job-id | Job | RFC 2911 |
| job-name | Job/operation | RFC 2911 |
| job-originating-user-name | Job | RFC 2911 |
| job-printer-up-time | Job | RFC 2911 |
| job-state | Job | RFC 2911 |
| job-state-reasons | Job | RFC 2911 |
| job-state-message | Job | RFC 2911 |
| limit | operation | RFC 2911 |
| my-jobs | operation | RFC 2911 |
| natural-language-configured | Printer | RFC 2911 |
| operations-supported | Printer | RFC 2911 |
| pdl-override-supported | Printer | RFC 2911 |
| pdl-override-guaranteed-supported | Printer | IANA |
| printer-is-accepting-jobs | Printer | RFC 2911 |
| printer-name | Printer | RFC 2911 |
| printer-state | Printer | RFC 2911 |
| printer-state-message | Printer | RFC 2911 |
| printer-state-reasons | Printer | RFC 2911 |
| printer-current-time | Printer | RFC 2911 |
| printer-up-time | Printer | RFC 2911 |
| printer-uri | operation | RFC 2911 |
| printer-uri-supported | Printer | RFC 2911 |
| queued-job-count | Printer | RFC 2911 |
| requested-attributes | operation | RFC 2911 |
| requesting-user-name | operation | RFC 2911 |
| date-time-at-completed | Job | RFC 2911 |
| date-time-at-creation | Job | RFC 2911 |
| date-time-at-processing | Job | RFC 2911 |
| time-at-completed | Job | RFC 2911 |
| time-at-creation | Job | RFC 2911 |
| time-at-processing | Job | RFC 2911 |
| uri-authentication-supported | Printer | RFC 2911 |
| uri-security-supported | Printer | RFC 2911 |
| printer-xri-supported | Printer | RFC 3380 |
| which-jobs | operation | RFC 2911 |
| print-quality | Job | RFC 2911 |
| print-quality-default | Job | RFC 2911 |
| print-quality-supported | Job | RFC 2911 |
| color-supported | Printer | RFC 2911 |
| copies | Job | RFC 2911 |
| copies-default | Printer | RFC 2911 |
| copies-supported | Printer | RFC 2911 |
| finishings | Job | RFC 2911 |
| finishings-supported | Printer | RFC 2911 |
| finishings-default | Printer | RFC 2911 |
| job-creation-attributes-supported | Printer | PWG 5100.11 |
| printer-alert | Printer | PWG 5100.9 |
| printer-alert-description | Printer | PWG 5100.9 |
| printer-info | Printer | RFC 2911 |
| printer-location | Printer | RFC 2911 |
| printer-geo-location | Printer | PWG 5100.13 |
| printer-make-and-model | Printer | RFC 2911 |
| printer-more-info | Printer | RFC 2911 |
| status-message | operation | RFC 2911 |
| ippget-event-life | Printer | RFC 3996 |
| job-hold-until | Job | RFC 2911 |
| job-hold-until-supported | Printer | RFC 2911 |
| job-hold-until-default | Printer | RFC 2911 |
| job-ids | operation | PWG 5100.11 |
| job-ids-supported | Printer | PWG 5100.11 |
| job-priority | Job | RFC 2911 |
| job-priority-default | Printer | RFC 2911 |
| job-priority-supported | Printer | RFC 2911 |
| job-settable-attributes-supported | Printer | RFC 3380 |
| printer-settable-attributes-supported | Printer | RFC 3380 |
| last-document | operation | RFC 2911 |
| multiple-operation-time-out | Printer | RFC 2911 |
| multiple-operation-time-out-action | Printer | PWG 5100.13 |
| notify-charset | Subscription | RFC 3995 |
| notify-events | Subscription | RFC 3995 |
| notify-events-default | Printer | RFC 3995 |
| notify-events-supported | Printer | RFC 3995 |
| notify-get-interval | operation | RFC 3996 |
| notify-job-id | Subscription | RFC 3995 |
| notify-lease-duration | Subscription | RFC 3995 |
| notify-lease-duration-default | Printer | RFC 3995 |
| notify-lease-duration-supported | Printer | RFC 3995 |
| notify-lease-expiration-time | Subscription | RFC 3995 |
| notify-max-events-supported | Printer | RFC 3995 |
| notify-natural-language | Subscription | RFC 3995 |
| notify-printer-up-time | Subscription | RFC 3995 |
| notify-printer-uri | Subscription | RFC 3995 |
| notify-pull-method | Subscription | RFC 3995 |
| notify-pull-method-supported | Printer | RFC 3995 |
| notify-sequence-number | Subscription | RFC 3995 |
| notify-sequence-numbers | operation | RFC 3995 |
| notify-status-code | operation | RFC 3995 |
| notify-subscribed-event | Subscription | RFC 3995 |
| notify-subscriber-user-name | Subscription | RFC 3995 |
| notify-subscription-id | Subscription | RFC 3995 |
| notify-subscriptions-ids | operation | RFC 3996 |
| notify-text | Subscription | RFC 3995 |
| notify-time-interval | Subscription | RFC 3995 |
| notify-user-data | Subscription | RFC 3995 |
| notify-wait | operation | RFC 3996 |
| output-device-supported | Printer | RFC 2911 |
| output-device-assigned | Job | RFC 3998 |
| printer-state-change-date-time | Printer | RFC 3995 |
| printer-state-change-time | Printer | RFC 3995 |
| printer-config-change-date-time | Printer | PWG 5100.13 |
| printer-config-change-time | Printer | PWG 5100.13 |
| which-jobs-supported | Printer | PWG 5100.11 |
| printer-get-attributes-supported | Printer | PWG 5100.13 |
| printer-icons | Printer | PWG 5100.13 |
| printer-organization | Printer | PWG 5100.13 |
| printer-organizational-unit | Printer | PWG 5100.13 |
| printer-uuid | Printer | PWG 5100.13 |
| job-uuid | Job | PWG 5100.13 |
| notify-subscription-uuid | Subscription | PWG 5100.13 |
| printer-mandatory-job-attributes | Printer | PWG 5100.13 |
| printer-supply | Printer | PWG 5100.13 |
| printer-supply-description | Printer | PWG 5100.13 |
| printer-supply-info-uri | Printer | PWG 5100.13 |
| compression-accepted | operation | PWG 5100.17 |
| document-format-accepted | operation | PWG 5100.17 |
| document-number | operation | PWG 5100.5 |
| document-preprocessed | operation | PWG 5100.18 |
| document-uri | operation | RFC 2911 |
| fetch-status-code | operation | PWG 5100.18 |
| fetch-status-message | operation | PWG 5100.18 |
| first-index | operation | PWG 5100.13 |
| identify-actions | operation | PWG 5100.13 |
| identify-actions-default | Printer | PWG 5100.13 |
| identify-actions-supported | Printer | PWG 5100.13 |
| output-device-job-states | operation | PWG 5100.18 |
| output-device-uuid | operation | PWG 5100.18 |
| printer-static-resource-directory-uri | Printer | PWG 5100.18 |
| printer-static-resource-k-octets-supported | Printer | PWG 5100.18 |
| printer-static-resource-k-octets-free | Printer | PWG 5100.18 |

* 1. 3D Printer Subunits

Table 4 lists the subunits of 3D printers for different technologies.

Table - 3D Printer Subunits

| **Subunit** | **Technology** | **Reference** |
| --- | --- | --- |
| Build Platforms | All | <none> |
| Cameras | All | <none> |
| Chamber | All | <none> |
| Cutters | SDL | RFC 3806 |
| Doors | All | RFC 3805 |
| Fans | FDM | <none> |
| Input Trays | SDL | RFC 3805 |
| Lamps | DLP | <none> |
| Lasers | Laser Sintering, SL | <none> |
| Marker Supplies | All | RFC 3805 |
| Markers (or Extruders) | Many | RFC 3805 |
| Media Path | SDL | RFC 3805 |
| Motors | All | <none> |
| Reservoirs | DLP, Laser Sintering, SL | <none> |

* + 1. Build Platforms

Build Platforms hold the printed object. The platform typically moves up or down during printing as layers are applied, although in some cases it moves along all three axis.

* + 1. Cameras

Cameras typically show the Build Platforms, offering a visual progress/status reporting for remote users.

* + 1. Chambers

Chambers are the volumes containing the objects being printed. Chambers are sometimes temperature controlled and/or have doors that provide access to the printed objects.

* + 1. Cutters

Cutters are used to trim support material on printed objects and/or remove regions of media that are not part of the final printed object.

* + 1. Fans

Fans are used to cool printed material and maintain proper extruder and material temperatures.

* + 1. Lamps

Lamps are used by DLP printers to provide an ultraviolet light source for curing the liquid material while printing a layer. Lamps are also used to illuminate the Build Platforms.

* + 1. Lasers

Lasers are used by Laser Sintering and Stereo Lithography (SL) printers to fuse powdered material or cure liquid material while printing a layer.

* + 1. Markers (or Extruders)

Markers can be traditional subunits where an image is printed on sheets of paper (SDL), extruders that place material onto the Build Platform or previous layer, or projectors that display an inverse image on the surface of a liquid material (DLP).

* + 1. Motors

Motors are used to move the Build Platforms and (in some cases) move the Markers.

* + 1. Reservoirs

Reservoirs hold liquid or powdered material used to create the printed object.

* 1. 3D Printer Coordinate System

3D printers operate in three dimensions and thus have three axis of movement. Figure 2 shows a typical coordinate system where the X axis represents the width of the object, the Y axis represents the depth of the object, and the Z axis represents the height of the object. Note that, depending on the technology used, the Z axis may move in the opposite direction, or the extruder may move independently with a stationary build platform.



Figure - Typical Build Platform Coordinate System

Filament usage by extrusion Printers is sometimes also modeled as an additional "E" axis, e.g., E1 for the first filament, E2 for the second filament, etc.

The Printer's coordinate system is often different than the coordinate system used in the ODL file to describe the object(s) being printed. The ODL interpreter on the Printer is responsible for performing any transformations needed to prepare the geometry for slicing in the Printer's coordinate system.

* 1. Output Intent and Job Processing

As with 2D printing, the focus of 3D printing using IPP is specification of output intent and not for process or device control. Clients can specify general material selections (“red PLA”, “brown wood PLA”, “clear ABS”, etc.), print speed and quality, build platform and chamber temperatures, and whether supports and rafts should be printed. Printers then use the implementation specific device control and (ordered) processes to satisfy the Client-supplied output intent when processing the Job.

Also as with 2D printing, 3D Printers process Jobs using one or more interpreters. 2D printing typically involves rasterization of the document data while 3D printing involves geometric transformations, addition of support geometry, and slicing (laying) of the object(s) in the document data so that they can be printed.

* 1. Job Spooling

Because common ODL formats are not designed to be incrementally processed as a stream of data, 3D printers will likely only support spooled (stored) processing of Jobs and Documents.

* 1. Cloud-Based Printing

Cloud-based printing can be supported by the existing IPP Shared Infrastructure Extensions (INFRA) [PWG5100.18]. Infrastructure Printers might require additional configuration or selection of drivers for the printer being configured, however that is outside the scope of this white paper and can be considered a part of provisioning the Cloud Service.

Snapshots of camera video can be uploaded as JPEG image resources using HTTP PUT requests from the Proxy to the Infrastructure Printer. Such resources need to be updated in an atomic fashion to allow Clients to safely poll for updates to the camera video.

1. New Attributes
   1. Job Template Attributes

Table 5 lists the Job Template attributes and their corresponding “–default” and “-supported” attributes.

Table - Job Template Attributes

| **Job Template** | **Printer: Default** | **Printer: Supported** |
| --- | --- | --- |
| materials-col (collection) | materials-col-default (1setOf collection) | materials-col-database (1setOf collection)  materials-col-ready (1setOf collection)  materials-col-supported (1setOf type2 keyword) |
| print-fill-density (integer(0:100) | print-fill-density-default (integer(0:100)) | <none> |
| print-fill-thickness (integer(0:MAX) | print-fill-thickness-default (integer(0:MAX)) | print-fill-thickness-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX))) |
| print-layer-thickness (integer(0:MAX)) | print-layer-thickness-default (integer(0:MAX)) | print-layer-thickness-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX))) |
| print-rafts (type2 keyword) | print-rafts-default (type2 keyword) | print-rafts-supported (1setOf type2 keyword) |
| print-shell-thickness (integer(0:MAX)) | print-shell-thickness-default (integer(0:MAX)) | print-shell-thickness-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX))) |
| print-speed (integer(1:MAX)) | print-speed-default (integer(1:MAX)) | print-speed-supported (1setOf (integer(1:MAX) | rangeOfInteger(1:MAX))) |
| print-supports (type2 keyword) | print-supports-default (type2 keyword) | print-supports-supported (1setOf type2 keyword) |
| printer-bed-temperature (integer | no-value) | printer-bed-temperature-default (integer | no-value) | printer-bed-temperature-supported (1setOf (integer | rangeOfInteger) | no-value) |
| printer-chamber-temperature (integer | no-value) | printer-chamber-temperature-default (integer | no-value) | printer-chamber-temperature-supported (1setOf (integer | rangeOfInteger) | no-value) |
| printer-fan-speed (integer(0:100)) | printer-fan-speed-default (integer(0:100)) | printer-fan-speed-supported (boolean) |

* + 1. materials-col (1setOf collection)

This Job Template attribute defines the materials to be used for the Job. When specified, the Printer validates the requested materials both when the Job is created and when it enters the 'processing' state. If the requested materials are not loaded, the 'material-needed' keyword is added to the Printer's "printer-state-reasons" values and the Job is placed in the 'processing-stopped' state.

The Client typically supplies "materials-col" values matching those returned in the "materials-col-database" (section 5.3.1) or "materials-col-ready" (section 5.3.10) Printer Description attributes. Table 6 lists the member attributes.

Table 6 - "materials-col" Member Attributes

| **Member Attribute** | **Printer: Supported Values** |
| --- | --- |
| material-amount | N/A |
| material-amount-units | material-amount-units-supported |
| material-color | N/A |
| material-diameter | material-diameter-supported |
| material-key | materials-col-database  materials-col-ready |
| material-name | materials-col-database  materials-col-ready |
| material-purpose | material-purpose-supported |
| material-rate | material-rate-supported |
| material-rate-units | material-rate-units-supported |
| material-temperate | material-temperature-supported |
| material-type | material-type-supported |

* + - 1. material-amount (integer(0:MAX) | unknown)

This member attribute provides the estimated amount of material that is available ("materials-col-database" and "materials-col-ready" values), the estimated amount of material that is required ("materials-col" values), or the actual amount of material that has been used ("materials-col-actual" values).

* + - 1. material-amount-units (type2 keyword)

This member attribute provides the units for the "material-amount" value. Values include:

'g': Value is mass in grams.

'kg': Value is mass in kilograms.

'l': Value is volume in liters.

'm': Value is length in meters.

'ml': Value is volume in milliliters.

'mm': Value is length in millimeters.

* + - 1. material-color (type2 keyword)

This member attribute provides a PWG media color value representing the color of the material.

material-diameter (integer(1:MAX))

This member attribute provides the diameter of the filament in nanometers and is only used for filament materials.

* + - 1. material-key (keyword)

This member attribute provides an unlocalized name of the material that can be localized using the strings file referenced by the "printer-strings-uri" Printer attribute.

* + - 1. material-name (name(MAX))

This member attribute provides a localized name of the material.

* + - 1. material-purpose (1setOf type2 keyword)

This member attribute specifies what the material will be used for. Values include:

'all': The material will be used for all parts of the printed object.

‘in-fill’: The material will be used to fill the interior of the printed object.

‘raft’: The material will be used to print a raft under the printed object.

‘shell’: The material will be used for the surface of the printed object.

‘support’: The material will be used to support the printed object.

* + - 1. material-rate (integer(1:MAX))

This member attribute provides the flow rate of the material per second. The units are defined by the "material-rate-units" member attribute.

* + - 1. material-rate-units (type2 keyword)

This member attribute provides the units for the "material-rate" member attribute. Values include:

'mg': Value is milligrams per second.

'ml': Value is milliliters per second.

'mm': Value is millimeters per second.

* + - 1. material-temperature (integer(-273:MAX) | rangeOfInteger(-273:MAX))

This member attribute specifies the temperature (or range of temperatures) for the material in degrees Celsius.

* + - 1. material-type (type2 keyword)

This member attribute specifies the type of material. The keyword consists of a material name (‘abs’, ‘pla’, ‘pla-flexible’, etc.) and form (‘filament’, ‘liquid’, ‘powder’, etc.) separated by an underscore. Material names and forms cannot contain the underscore (\_) character, which is reserved as a separator in the keyword value. Values include:

'abs\_filament': Acrylonitrile Butadiene Styrene (ABS) filament.

‘abs-carbon-fiber\_filament’: ABS filament reinforced with carbon fibers.

‘abs-carbon-nanotube\_filament’: ABS filament reinforced with carbon nanotubes.

'chocolate\_powder': Chocolate powder.

'gold\_powder': Gold (metal) powder.

‘nylon\_filament’: Nylon filament.

‘pet\_filament’: Polyethylene terephthalate (PET) filament.

'photopolymer-resin\_liquid': Photopolymer (liquid) resin.

'pla\_filament': Polylactic Acid (PLA) filament.

'pla-conductive\_filament': Conductive PLA filament.

‘pla-dissolvable\_filament’: Dissolvable PLA filament.

'pla-flexible\_filament': Flexible PLA filament.

‘pla-magnetic\_filament’: PLA with embedded iron particles.

‘pla-steel-filament’: PLA with embedded steel particles.

‘pla-stone\_filament’: PLA filament with embedded stone chips.

‘pla-wood\_filament’: PLA filament with embedded wood fibers.

‘polycarbonate\_filament’: Polycarbonate filament.

'silver\_powder': Silver (metal) powder.

‘titanium\_powder’: Titanium (metal) powder.

'wax\_solid': Solid wax.

* + 1. print-fill-density (integer(0:100))

This Job Template attribute specifies the in-fill density of interior regions in percent.

* + 1. print-fill-thickness (integer(0:MAX))

This Job Template attribute specifies the thickness of any in-fill walls in nanometers, with 0 representing the thinnest possible walls.

* + 1. print-layer-thickness (integer(0:MAX))

This Job Template attribute specifies the thickness of each layer in nanometers, with 0 representing the thinnest possible layers.

* + 1. print-rafts (type2 keyword)

This Job Template attribute specifies whether to print brims, rafts, or skirts under the object. Values include:

'none': Do not print brims, rafts, or skirts.

‘brim': Print brims using the ‘raft’ material specified for the Job.

‘raft': Print rafts using the ‘raft’ material specified for the Job.

‘skirt': Print skirts using the ‘raft’ material specified for the Job.

'standard': Print brims, rafts, and/or skirts using implementation-defined default parameters.

* + 1. print-shell-thickness (integer(0:MAX))

This Job Template attribute specifies the thickness of exterior walls in nanometers, with 0 representing the thinnest possible wall.

* + 1. print-speed (integer(1:MAX))

This Job Template attribute specifies the printing speed in nanometers per second.

* + 1. print-supports (type2 keyword)

This Job Template attribute specifies whether to print supports under the object. Values include:

'none': Do not print supports.

'standard': Print supports using implementation-defined default parameters.

'material': Print supports using the ‘support’ material specified for the Job.

* + 1. printer-chamber-temperature (integer(-273:MAX) | no-value)

This Job Template attribute specifies the desired print chamber temperature in degrees Celsius. The 'no-value' value is used to disable temperature control in the print chamber.

* + 1. printer-fan-speed (integer(0:100))

This Job Template attribute specifies the desired fan speed in percent of maximum. A value of 0 turns the fans off during printing.

* + 1. printer-platform-temperature (integer(-273:MAX) | no-value)

This Job Template attribute specifies the desired Build Platform temperature in degrees Celsius. The 'no-value' value is used to disable temperature control on the Build Platform.

* 1. Job Description Attributes
     1. materials-col-actual (1setOf collection)

This Job Description attribute provides a receipt of the actual material(s) used for the Job.

* 1. Printer Description Attributes
     1. material-amount-units-supported (1setOf type2 keyword)

This Printer Description attribute lists the supported "material-amount-units" values for the Printer.

* + 1. material-diameter-supported (1setOf (integer | rangeOfInteger))

This Printer Description attribute lists the supported "material-diameter" values for the Printer.

* + 1. material-purpose-supported (1setOf type2 keyword)

This Printer Description attribute lists the supported “material-purpose” values for the Printer.

* + 1. material-rate-supported (1setOf (integer | rangeOfInteger)

This Printer Description attribute lists the supported "material-rate" values for the Printer.

* + 1. material-rate-units-supported (1setOf type2 keyword)

This Printer Description attribute lists the supported "material-rate-units" values for the Printer.

* + 1. material-temperature-supported (1setOf (integer(-273:MAX) | rangeOfInteger(-273:MAX)))

This Printer Description attribute specifies the supported "material-temperature" values (or ranges of values) in degrees Celsius.

* + 1. material-type-supported (1setOf type2 keyword)

This Printer Description attribute lists the supported “material-type” values for the Printer.

* + 1. materials-col-database (1setOf collection)

This Printer Description attribute lists the pre-configured materials for the Printer. Each value contains the corresponding "materials-col" member attributes and will typically reflect vendor and site ("third party") materials that are supported by the Printer.

* + 1. materials-col-default (1setOf collection)

This Printer Description attribute lists the default materials that will be used if the "materials-col" Job Template attribute is not specified.

* + 1. materials-col-ready (1setOf collection)

This Printer Description attribute lists the materials that have been loaded into the Printer. Each value contains the corresponding "materials-col" member attributes.

* + 1. materials-col-supported (1setOf type2 keyword)

This Printer Description attribute lists the "materials-col" member attributes that are supported by the Printer.

* + 1. print-fill-density-default (integer(0:100))

This Printer Description attribute specifies the default "print-fill-density" value in percent.

* + 1. print-fill-thickness-default (integer(0:MAX))

This Printer Description attribute specifies the default "print-fill-thickness" value in nanometers.

* + 1. print-fill-thickness-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX)))

This Printer Description attribute lists the supported "print-fill-thickness" values (or ranges of values) in nanometers.

* + 1. print-layer-order (type1 keyword)

This Printer Description attribute specifies the order of layers when printing, either 'top-to-bottom' or 'bottom-to-top'.

* + 1. print-layer-thickness-default (integer(0:MAX))

This Printer Description attribute specifies the default "print-layer-thickness" value in nanometers.

* + 1. print-layer-thickness-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX)))

This Printer Description attribute lists the supported values (or ranges of values) for the "print-layer-thickness" Job Template attribute.

* + 1. print-rafts-default (type2 keyword)

This Printer Description attribute specifies the default "print-rafts" value.

* + 1. print-rafts-supported (1setOf type2 keyword)

This Printer Description attribute lists the supported "print-rafts" values.

* + 1. print-shell-thickness-default (integer(0:MAX))

This Printer Description attribute specifies the default "print-shell-thickness" value in nanometers.

* + 1. print-shell-thickness-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX)))

This Printer Description attribute lists the supported "print-shell-thickness" values (or ranges of values) in nanometers.

* + 1. print-speed-default (integer(1:MAX))

This Printer Description attribute lists the default "print-speed" value in nanometers per second.

* + 1. print-speed-supported (1setOf (integer(1:MAX) | rangeOfInteger(1:MAX)))

This Printer Description attribute lists the supported "print-speed" values (or ranges of values) in nanometers per second.

* + 1. print-supports-default (type2 keyword)

This Printer Description attribute specifies the default "print-supports" value.

* + 1. print-supports-supported (1setOf type2 keyword)

This Printer Description attribute lists the supported "print-supports" values.

* + 1. printer-accuracy-supported (collection)

This Printer Description attribute specifies the absolute accuracy of the Printer. The "x-accuracy (integer(1:MAX))", "y-accuracy (integer(1:MAX))", and "z-accuracy (integer(1:MAX))" member attributes specify the accuracy in nanometers along each axis.

* + 1. printer-camera-image-uri (1setOf uri)

This Printer Description attribute lists the URIs for one or more resident camera snapshots. Each URI corresponds to a separate resident camera. The images referenced by each URI can change at any time so it is up to the Client to periodically poll for changes and for the Printer to atomically update the images so that Clients can safely do so.

* + 1. printer-chamber-temperature-default (integer(-273:MAX) | no-value)

This Printer Description attribute specifies the default "printer-chamber-temperature" value in degrees Celsius.

* + 1. printer-chamber-temperature-supported (1setOf (integer(-273:MAX) | rangeOfInteger(-273:MAX)) | no-value)

This Printer Description attribute lists the supported "printer-chamber-temperature" values (or ranges of values) in degrees Celsius. The out-of-band 'no-value' value specifies that the Printer does not offer temperature control of the print chamber.

* + 1. printer-fan-speed-default (integer(0:MAX))

This Printer Description attribute specifies the default "printer-fan-speed" value in percent.

* + 1. printer-fan-speed-supported (boolean)

This Printer Description attribute specifies whether the "printer-fan-speed" Job Template attribute is supported.

* + 1. printer-platform-temperature-default (integer(-273:MAX) | no-value)

This Printer Description attribute specifies the default "printer-platform-temperature" value in degrees Celsius.

* + 1. printer-platform-temperature-supported (1setOf (integer(-273:MAX) | rangeOfInteger(-273:MAX)) | no-value)

This Printer Description attribute lists the supported "printer-platform-temperature" values (or ranges of values) in degrees Celsius. The out-of-band 'no-value' value specifies that the Printer does not offer temperature control of the Build Platform.

* + 1. printer-volume-supported (collection)

This Printer Description attribute specifies the maximum build volume supported by the Printer. The "x-dimension (integer(1:MAX))", "y-dimension (integer(1:MAX))", and "z-dimension (integer(1:MAX))" member attributes specify the size in millimeters along each axis.

* 1. Printer Status Attributes

[Editor's note: May be useful to change these to pairs of printer-xxx and printer-xxx-description attributes, like we do for printer-alert, printer-input-tray, printer-output-tray, printer-supply, etc. That will also provide a mapping to potential MIB extensions...]

* + 1. printer-chamber-temperature-current (integer | no-value)

This Printer Status attribute provides the current print chamber temperature in degrees Celsius. If the print chamber is not temperature controlled, the 'no-value' value is returned.

* + 1. printer-fan-speed-current (integer(0:100))

This Printer Status attribute provides the current fan speed in percent.

* + 1. printer-head-temperature-current (1setOf (integer | no-value))

This Printer Status attribute provides the current extruder head temperatures in degrees Celsius. The 'no-value' value is returned when the extruder head is not temperature controlled.

* + 1. printer-platform-temperature-current (integer(-273:MAX) | no-value)

This Printer Status attribute provides the current Build Platform temperature in degrees Celsius. If the Build Platform is not temperature controlled, the 'no-value' value is returned.

1. New Values for Existing Attributes
   1. ipp-features-supported (1setOf type2 keyword)

This document suggests (but does not register) the new value 'ipp-3d'.

* 1. printer-state-reasons (1setOf type2 keyword)

This document suggests (but does not register) the following new values:

'camera-failure': A camera is no longer working.

'chamber-cooling': A chamber is being cooled.

'chamber-heating': A chamber is being heated.

'chamber-temperature-high': The temperature of a chamber is high.

'chamber-temperature-low': The temperature of a chamber is low.

'cutter-at-eol': A cutter has reached its end-of-life and will need to be replaced soon.

'cutter-failure': A cutter has failed.

'cutter-near-eol': A cutter is near its end-of-life and may need to be replaced soon.

'extruder-cooling': An extruder is being cooled.

'extruder-failure': An extruder has failed and requires maintenance or replacement.

'extruder-heating': An extruder is being heated.

'extruder-jam': An extruder is jammed or clogged.

'extruder-temperature-high': The temperature of an extruder is too high.

'extruder-temperature-low': The temperature of an extruder is too low.

'fan-failure': A fan has failed.

'lamp-at-eol': A lamp has reached its end-of-life and will need to be replaced soon.

'lamp-failure': A lamp has failed.

'lamp-near-eol': A lamp is near its end-of-life and may need to be replaced soon.

'laser-at-eol': A laser has reached its end-of-life and will need to be replaced soon.

'laser-failure': A laser has failed.

'laser-near-eol': A laser is near its end-of-life and may need to be replaced soon.

'material-empty': One or more build materials have been exhausted.

'material-low': One or more build materials may need replenishment soon.

'material-needed': One or more build materials need to be loaded for a processing Job.

'motor-failure': A motor has failed.

'reservoir-empty': One or more reservoirs are empty.

'reservoir-low': One or more reservoirs are almost empty.

'reservoir-needed': One or more reservoirs are empty but need to be filled for a processing Job.

[Editor's Note: Additional keywords may be needed, for discussion]

1. Object Definition Languages (ODLs)

This section provides information on several commonly used ODLs with either existing (registered) or suggested MIME media types.

* 1. 3D Manufacturing Format (3MF)

3MF [3MF] is a freely-available format based on the Open Packaging Conventions that provides geometry, material, and texture information necessary to support a wide variety of 3D printers. Materials can be named and composed within the geometry, facilitating multiple material support in coordination with a Job Ticket.

The registered MIME media type for the original Microsoft published specification is "application/vnd.ms-3mfdocument". The suggested (but not registered) MIME media type for the 3MF Consortium's published specification is "model/3mf".

* 1. Additive Manufacturing Format (AMF)

AMF [ISO52915] is a relatively new format that was designed as a replacement for the Standard Tessellation Language (STL). Its use has been hampered by the lack of a freely-available specification, but has several advantages over STL including:

1. Shared vertices which eliminates holes and other breaks in the surface geometry of objects,
2. Specification of multiple materials in a single file,
3. Curved surfaces can be specified, and
4. Coordinates use explicit units for proper output dimensions.

The suggested (but not registered) MIME media type is model/amf'.

* 1. Standard Tessellation Language (STL)

STL [STLFORMAT] is widely supported by existing client software. The registered MIME media type is 'application/sla'.

1. Internationalization Considerations

For interoperability and basic support for multiple languages, conforming implementations MUST support:

1. The Universal Character Set (UCS) Transformation Format -- 8 bit (UTF-8) [STD63] encoding of Unicode [UNICODE] [ISO10646]; and
2. The Unicode Format for Network Interchange [RFC5198] which requires transmission of well-formed UTF-8 strings and recommends transmission of normalized UTF-8 strings in Normalization Form C (NFC) [UAX15].

Unicode NFC is defined as the result of performing Canonical Decomposition (into base characters and combining marks) followed by Canonical Composition (into canonical composed characters wherever Unicode has assigned them).

WARNING – Performing normalization on UTF-8 strings received from IPP Clients and subsequently storing the results (e.g., in IPP Job objects) could cause false negatives in IPP Client searches and failed access (e.g., to IPP Printers with percent-encoded UTF-8 URIs now 'hidden').

Implementations of this document SHOULD conform to the following standards on processing of human-readable Unicode text strings, see:

Unicode Bidirectional Algorithm [UAX9] – left-to-right, right-to-left, and vertical

Unicode Line Breaking Algorithm [UAX14] – character classes and wrapping

Unicode Normalization Forms [UAX15] – especially NFC for [RFC5198]

Unicode Text Segmentation [UAX29] – grapheme clusters, words, sentences

Unicode Identifier and Pattern Syntax [UAX31] – identifier use and normalization

Unicode Character Encoding Model [UTR17] – multi-layer character model

Unicode in XML and other Markup Languages [UTR20] – XML usage

Unicode Character Property Model [UTR23] – character properties

Unicode Conformance Model [UTR33] – Unicode conformance basis+

Unicode Collation Algorithm [UTS10] – sorting

Unicode Locale Data Markup Language [UTS35] – locale databases

1. Security Considerations

In addition to the security considerations described in the IPP/1.1: Model and Semantics [RFC2911], the following sub-sections describe issues that are unique to 3D printing.

Implementations of this specification SHOULD conform to the following standards on processing of human-readable Unicode text strings, see:

Unicode Security Mechanisms [UTS39] – detecting and avoiding security attacks

Unicode Security FAQ [UNISECFAQ] – common Unicode security issues

* 1. Access Control

Because of the potential for abuse and misuse, Printers SHOULD provide access control mechanisms including lists of allowed Clients, authentication, and authorization to site defined policies.

* 1. Physical Safety

Printers MUST NOT allow Clients to disable physical safety features of the hardware, such as protective gates, covers, or interlocks.

* 1. Material Safety

Printers MUST restrict usage and combination of materials to those that can be safely printed. Access controls (section 9.1) MAY be used to allow authorized users to experiment with untested materials or combinations, but only when such materials or combinations can reasonably be expected to not pose a safety risk.

* 1. Temperature Control

Printers MUST validate temperature and fan speed values provided by Clients and limit material, extruder, build platform, and print chamber temperatures within designed limits to prevent unsafe operating conditions, damage to the hardware, explosions, and/or fires.

1. References

[3MF] "3D Manufacturing Format Core Specification & Reference Guide v1.0", http://www.3mf.io/wp-content/uploads/2015/04/3MFcoreSpec\_1.0.1.pdf

[ISO10646] "Information technology -- Universal Coded Character Set (UCS)", ISO/IEC 10646:2011

[ISO52915] "Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1", ISO/ASTM 52915, 2013

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[PWG5100.11]

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[PWG5100.14] M. Sweet, I. McDonald, A. Mitchell, J. Hutchings, "IPP Everywhere", PWG 5100.14, January 2013, <http://ftp.pwg.org/pub/pwg/candidates/cs-ippeve10-20130128-5100.14.pdf>

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[RFC2911] T. Hastings, R. Herriot, R. deBry, S. Isaacson, P. Powell, "Internet Printing Protocol/1.1: Model and Semantics", RFC 2911, September 2000, <http://tools.ietf.org/html/rfc2911>

[RFC3805] R. Bergman, H. Lewis, I. McDonald, "Printer MIB v2", RFC 3805, June 2004, <http://tools.ietf.org/html/rfc3805>

[RFC3806] R. Bergman, H. Lewis, I. McDonald, "Printer Finishing MIB", RFC 3806, June 2004, <http://tools.ietf.org/html/rfc3806>

[RFC5198] J. Klensin, M. Padlipsky, "Unicode Format for Network Interchange", RFC 5198, March 2008, <http://tools.ietf.org/html/rfc5198>

[STD63] F. Yergeau, "UTF-8, a transformation format of ISO 10646", RFC 3629/STD 63, November 2003, <http://tools.ietf.org/html/rfc3629>

[STLFORMAT] 3D Systems, Inc., "SLC File Specification", 1994

[UAX9] Unicode Consortium, “Unicode Bidirectional Algorithm”, UAX#9, June 2014,  
<http://www.unicode.org/reports/tr9/tr9-31.html>

[UAX14] Unicode Consortium, “Unicode Line Breaking Algorithm”, UAX#14, June 2014,  
<http://www.unicode.org/reports/tr14/tr14-33.html>

[UAX15] Unicode Consortium, “Normalization Forms”, UAX#15, June 2014,   
<http://www.unicode.org/reports/tr15/tr15-41.html>

[UAX29] Unicode Consortium, “Unicode Text Segmentation”, UAX#29, June 2014,   
<http://www.unicode.org/reports/tr29/tr29-25.html>

[UAX31] Unicode Consortium, “Unicode Identifier and Pattern Syntax”, UAX#31, June 2014,  
<http://www.unicode.org/reports/tr31/tr31-21.html>

[UNICODE] Unicode Consortium, "Unicode Standard", Version 7.0.0, June 2014,   
<http://www.unicode.org/versions/Unicode7.0.0/>

[UNISECFAQ] Unicode Consortium “Unicode Security FAQ”, November 2013,  
<http://www.unicode.org/faq/security.html>

[UTR17] Unicode Consortium “Unicode Character Encoding Model”, UTR#17, November 2008,  
<http://www.unicode.org/reports/tr17/tr17-7.html>

[UTR20] Unicode Consortium “Unicode in XML and other Markup Languages”, UTR#20, January 2013,  
<http://www.unicode.org/reports/tr20/tr20-9.html>

[UTR23] Unicode Consortium “Unicode Character Property Model”, UTR#23, November 2008,  
<http://www.unicode.org/reports/tr23/tr23-9.html>

[UTR33] Unicode Consortium “Unicode Conformance Model”, UTR#33, November 2008,  
<http://www.unicode.org/reports/tr33/tr33-5.html>

[UTS10] Unicode Consortium, “Unicode Collation Algorithm”, UTS#10, June 2014,  
http://www.unicode.org/reports/tr10/tr10-30.html,

[UTS35] Unicode Consortium, “Unicode Locale Data Markup Language”, UTS#35, September 2014,  
<http://www.unicode.org/reports/tr35/tr35-37/tr35.html>

[UTS39] Unicode Consortium, “Unicode Security Mechanisms”, UTS#39, September 2014,  
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1. Change History
   1. November 16, 2015
2. Section 1: Fix typos
3. Section 3: Updated rationale to talk about 3MF instead of AMF and STL
4. Section 4: Added new subsection on the 3D Print Service and the operations and attributes that are used.
5. Section 4.3: Added Chambers to list of subunits since we are providing access to the temperature.
6. Section 5.1.1: Added table listing all member attributes.
7. Section 5.1.1.x: Added sections on material-amount, material-amount-units, material-diameter, material-rate, material-rate-units
8. Section 5.1.1.x: Renamed "material-use" to "material-purpose" to avoid confusion with "material-amount-xxx".
9. Section 5.3: Add new materials-col member attribute -supported attributes
10. Section 7.1: Note existing MS 3DMF MIME media type
11. Global: printer-bed-xxx -> printer-platform-xxx
12. Global: Add range for all temperature attributes (-273:MAX)
    1. October 29, 2015
13. Greatly expanded the discussion of how current solutions work and the IPP model
14. Added discussion points for amount of material used
15. Added materials-col-actual Job Description attribute
16. Added 3MF description and reference
17. Fixed link to IPP Everywhere in references
    1. August 12, 2015
18. Dropped “0.1” from the title
19. Various typographical changes
20. Section 2.2: Added ODL acronym
21. Table 1: Added reference column
22. Figure 1: Updated figure to show Z increasing downward (direction of build platform movement)
23. Section 4.x: Added sub-section on output intent.
24. Section 5.1: Added table listing Job Template and corresponding -default and -supported attributes.
25. Section 5.1.1.4: Added more types of filament, solid wax, and clarification on the names used for material type keywords.
26. Section 5.1.1.5: Made material-use 1setOf, added 'all' value.
27. Updated printer-bed-temperature-supported and printer-chamber-temperature-supported to allow 'no-value' values.
28. Section 9.x: Added subsections on specific 3D printing security considerations.
    1. July 29, 2015
29. Dropped all references to X3G and G-code.
30. Reworked materials-col to specify materials but not temperatures and other physical properties
31. Added “material-use” member attribute to assign materials to specific uses.
32. Supports and rafts pick materials based on “material-use” values and not indices.
33. Added reference to IPP INFRA
34. Added printer-camera-image-uri Printer Description attribute.
    1. April 13, 2015
35. Updated front matter to incorporate new IEEE-ISTO boilerplate for a contributed white paper.
    1. April 5, 2015
36. Updated front matter to remove IEEE-ISTO boilerplate.
37. Fixed various typos
38. Clarified that SLC files are commonly known as STL files.
39. Clarified that S3G is a binary version of G-code with a standard packet format.
40. Added use case for printing with loaded materials
41. Added use case for multi-material printing on a single material printer.
42. Added use case for monitoring print progress visually with a web cam.
43. Added exception for "skipping" (insufficient material flow/feed)
44. Added exception for adhesion issues
45. Added exception for build plate being full.
46. Added exception for head movement issues.
47. Added figure showing the typical coordinate system.
48. Expanded Job Template and Printer Description details, added comments for discussion.
49. Added new Unicode considerations and references.
    1. January 23, 2015

Initial revision.