PWG Safe G-Code Subset for 3D Printing

Status: Prototype

Abstract: This Best Practice document defines a "safe" subset of G-code for use in 3D printing with IPP along with the capabilities and parameters needed to allow a client to generate G-code compatible with the printer.

This is a PWG Working Draft. For a definition of a "PWG Working Draft", see:


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Title:  *PWG Safe G-Code Subset for 3D Printing*

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1. Introduction

G-Code [ISO6893-1] [RS274D] [RS274NGC] [REPRAP] is a commonly-used format for 3D printing with so-called Fused Deposition Modeling (FDM) printers. Besides the commands used to move the print head and/or platform and to extrude material, G-Code includes a variety of device control (e.g., set extruder temperature) and hardware access (e.g., write file to SD card) commands that pose serious safety and security concerns. To make matters worse, such commands are often printer-specific or have printer-specific variations in syntax, requiring the equivalent of printer driver software to produce G-Code suitable for a particular model or firmware version. Finally, differences in filament and extruder nozzle diameters mean that G-Code created for one print job may not work on the same printer due to changes to the material or extruder.

The IPP 3D Printing Extensions v1.0 [PWG5100.21] define the model and semantics for networked 3D printing, along with a required high-level 3D file format. However, the processing requirements of such a format require either improved printer controllers with greater memory, storage, and CPU capacity or the use of Cloud services to offload that processing.

The IPP Shared Infrastructure Extensions (INFRA) [PWG5100.18] define the model and semantics for Cloud printing, however it does not specify an intermediate format suitable for 3D printing.

This document defines a "safe" subset of G-Code that can be used for direct and Cloud printing configurations, along with a description of the capabilities and parameters that will be needed to generate suitable layers for printing to the target printer.

The goal of this document is to enable the use of IPP with existing entry-level FDM printers that are not able to perform their own slicing and to enable generic Cloud and local infrastructure services to provide slicing services to existing FDM printers. Support for other kinds of 3D printers will likely require an intermediate format such as the 3MF Slice Extension [3MF-SLICE].
2. Terminology

2.1 Terms Used in This Document

Cloud: the environment supporting services such as Cloud Computing.

Cloud Computing: “... a model for enabling ubiquitous, convenient, on demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.” The NIST Definition of Cloud Computing [NISTSP800-145].

Fused Deposition Modeling: A 3D printing process that extrudes a molten material to draw layers, sometimes also called material extrusion.

2.2 Acronyms and Organizations

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


PWG: Printer Working Group, https://www.pwg.org/
3. PWG Safe G-Code Subset

This document defines a safe G-Code subset with the MIME Media Type "application/vnd.pwg-safe-gcode". Safe G-Code files consist solely of the following commands which represent the common subset of commands supported by most FDM printers:

- G0: Rapid Linear Move
- G1: Controlled Linear Move
- G4: Dwell
- G21: Set Units to Millimeters
- G28: Move to Origin (Home)
- G90: Set Absolute Positioning
- G91: Set Relative Positioning
- G92: Set Position
- M82: Set Absolute Extrusion
- M83: Set Relative Extrusion
- Tnnn: Set Tool

Most machine ("M") commands are not allowed since they directly control or access the machine hardware. Temperature control and other machine settings are the responsibility of the IPP Printer, which will likely use the IPP Job Template attribute values to send the corresponding printer-specific G-code commands to a lower-level controller.

The line number command ("N") and checksum ("*"*) are similarly not allowed because they are used for direct communications with the controller - IPP provides the necessary infrastructure for reliable communication of the G-Code file to the IPP Printer.

Comments starting with the ";;" character are allowed and continue to the end of the current line.

For simplicity, safe G-Code always uses millimeters for the units (the default).

3.1 G0 and G1: (Rapid/Controlled) Linear Move

These commands move the current tool (extruder) and/or extrude material for printing. Parameters for this command are:
Xnnn: Set X position in millimeters
Ynnn: Set Y position in millimeters
Znnn: Set Z position in millimeters
Ennn: Extrude the specified number of millimeters of material
Fnnn: Set the feed rate in millimeters/minute

Note: The "S" parameter is not allowed in safe G-Code.

3.2 G4: Dwell
This command pauses printing for a specifies amount of time. The "Pnnn" parameter specifies the time interval in milliseconds.

3.3 G21: Set Units to Millimeters
This command explicitly specifies that coordinates are in millimeters (the default).
Note: This command is only provided for completeness - there is no support in safe G-Code for any other units.

3.4 G28: Move to Origin (Home)
This command moves the current tool to the home position (end stops). The "X", "Y", and "Z" parameters may optionally be specified to move the tool on the specified axes - if not supplied the tool is moved on all axes.

3.5 G90: Set Absolute Positioning
This command specifies that all coordinates are relative to the origin of the machine.

3.6 G91: Set Relative Positioning
This command specifies that all coordinates are relative to the current position of the tool.

3.7 G92: Set Position
This command sets the current tool positions without moving or extruding material. Parameters for this command are:
Xnnn: Set X position in millimeters
Ynnn: Set Y position in millimeters
Znnn: Set Z position in millimeters
Ennn: Set extrusion to the specified number of millimeters of material

All positions are set to 0 if no parameters are specified.

3.8 M82: Set Absolute Extrusion

This command specifies that the extrusion ("E") coordinates in move commands are absolute.

3.9 M83: Set Relative Extrusion

This command specifies that the extrusion ("E") coordinates in move commands are relative.

3.10 Tnnn: Set Tool

This command sets the current tool (extruder) to use, starting at 0.

Editor's Note: Discuss how client maps tool numbers to materials.
4. Generating Safe G-Code

IPP Clients [STD92] and Infrastructure Printers [PWG5100.18] can generate safe G-Code using the values of Printer Description attributes reported by the IPP Printer or Proxy. Table 1 shows the information that is needed to generate safe G-Code for a printer. The "materials-col" values are obtained from the "materials-col-database" and/or "materials-col-ready" Printer Description attributes which provide a list of all possible materials and those that are loaded in the Printer, respectively.

<table>
<thead>
<tr>
<th>Description</th>
<th>Current IPP Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy limits/minimum layer height</td>
<td>print-accuracy-supported (collection)</td>
</tr>
<tr>
<td>Build platform dimensions</td>
<td>printer-volume-supported (collection)</td>
</tr>
<tr>
<td>Build platform shape</td>
<td>platform-shape (type2 keyword)</td>
</tr>
<tr>
<td>Extruder nozzle size/maximum layer height</td>
<td>See section Error! Reference source not found.</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>materials-col.material-diameter (integer)</td>
</tr>
<tr>
<td>Retraction support</td>
<td>See section Error! Reference source not found.</td>
</tr>
</tbody>
</table>

4.1 Material Extrusion Parameters

IPP 3D v1.0 [PWG5100.21] does not define attributes or values for the extruder nozzle size, nor does it define a way to specify whether retraction is used. These can be added to the "materials-col" collection as:

- "material-nozzle-diameter (integer(0:MAX))": Specifies the required extruder diameter in nanometers, with the value 0 indicating the nozzle diameter is less than 1 nanometer.
- "material-retraction (boolean)": Specifies whether retraction should be used with the material.

A corresponding "material-nozzle-diameter-supported (1setOf (integer(0:MAX) | rangeOfInteger(0:MAX)))" Printer Description attribute can provide the supported nozzle diameter values. The presence of 'material-retraction' in the "materials-col-supported" Printer Description attribute indicates that the Printer supports material retraction.

4.2 Support for Additional "Safe" G-Code Commands

In addition to the common subset of G-Code commands listed in the previous sections, newer FDM printers support additional "safe" commands such as mixing of extruded material ("M163", "M164", and "M165"), controlled arc ("G2" and "G3") and Bézier cubic spline ("G5"). In order for a generic slicer to support these commands, a printer needs to advertise its support for them. The usual method employed for IPP is a PDL-specific capability attribute,
such as "safe-gcode-supported (1setOf text(MAX))" with each value corresponding to a named command.

5. Printing Safe G-Code

Printers that support safe G-Code can largely pass the print file to the controller - typically all that is required is to add printer-specific commands to initialize the printer to set temperatures and other machine settings, send the print file, and then add printer-specific commands to return the printer to an idle state.

Status information returned by the printer can be used to set the values of the various IPP Printer Status attributes.

5.1 Adding Printer-Specific Machine Commands

IPP Job Template attributes provide the values for extruder and build platform temperatures, as well as the list of materials used in the print job. Table 2 lists the standard attributes a FDM printer can use to configure the machine prior to printing.

<table>
<thead>
<tr>
<th>Description</th>
<th>IPP Attribute(s)</th>
<th>Typical G-Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build platform temperature</td>
<td>platform-temperature</td>
<td>M140/M190</td>
</tr>
<tr>
<td>Chamber humidity</td>
<td>printer-volume-humidity</td>
<td>M146</td>
</tr>
<tr>
<td>Chamber temperature</td>
<td>printer-volume-temperature</td>
<td>M141/M191</td>
</tr>
<tr>
<td>Extruder nozzle size</td>
<td>materials-col/material-nozzle-diameter</td>
<td></td>
</tr>
<tr>
<td>Extruder temperature</td>
<td>materials-col/material-temperature</td>
<td>M104/M109</td>
</tr>
<tr>
<td>Filament color</td>
<td>materials-col/material-color</td>
<td></td>
</tr>
<tr>
<td>Filament diameter</td>
<td>materials-col/material-diameter</td>
<td>M200</td>
</tr>
<tr>
<td>Filament type</td>
<td>materials-col/material-type</td>
<td></td>
</tr>
<tr>
<td>Flow rate</td>
<td>materials-col/material-rate</td>
<td>M203</td>
</tr>
<tr>
<td>Job Name</td>
<td>job-name</td>
<td>M531</td>
</tr>
<tr>
<td>Print accuracy</td>
<td>print-accuracy</td>
<td>M201/M202/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M222/M223</td>
</tr>
<tr>
<td>Print quality/speed</td>
<td>print-quality</td>
<td></td>
</tr>
</tbody>
</table>

When an IPP Client does not specify one or more of these attributes, the corresponding default attribute values are used - "materials-col-default", "platform-temperature-default", "print-accuracy-default", "print-quality-default", "printer-volume-humidity-default", and "printer-volume-temperature-default" for the attributes in Table 2.
5.2 Printer-Specific Attributes and Values

IPP allows implementors to add printer-specific attributes and values as defined in section 7 of [STD92]. However, printers cannot depend on IPP Clients or Infrastructure Printers to support such attributes or values, particularly for generation of safe G-Code. Default values should be used as a backup when necessary.
6. IANA Considerations

6.1 Attribute Registrations

The attributes defined in this white paper will be published by IANA according to the procedures in IPP/1.1 Model and Semantics [STD92] section 7.2 in the following file:

https://www.iana.org/assignments/ipp-registrations

The registry entries will contain the following information:

Job Template attributes:

<table>
<thead>
<tr>
<th>Attribute Name</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>materials-col (lsetOf collection)</td>
<td>PWG5100.21</td>
</tr>
<tr>
<td>material-extruder-diameter (integer(0:MAX))</td>
<td>SAFEGCODE</td>
</tr>
<tr>
<td>material-retraction (boolean)</td>
<td>SAFEGCODE</td>
</tr>
</tbody>
</table>

Printer Description attributes:

<table>
<thead>
<tr>
<th>Attribute Name</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>material-extruder-diameter-supported (lsetOf (integer(0:MAX)</td>
<td>SAFEGCODE</td>
</tr>
<tr>
<td>rangeOfInteger(0:MAX))</td>
<td>SAFEGCODE</td>
</tr>
<tr>
<td>safe-gcode-supported (lsetOf text(MAX))</td>
<td>SAFEGCODE</td>
</tr>
</tbody>
</table>

6.2 MIME Media Type Registration

The MIME media type defined in this white paper will be published by IANA according to the procedures in the Media Type Specifications and Registration Procedures [BCP13] in the following file:

https://www.iana.org/assignments/media-types

The registry will contain the following information:

Type name: application

Subtype name: vnd.pwg-safe-gcode

Required parameters: N/A

Optional parameters: N/A

Encoding considerations: US ASCII

Security considerations: Safe G-code prohibits machine control commands, however it is up to the consumer to verify that such commands are not part of the print file.

Interoperability considerations: While the format is interoperable, the contents of each file are still specific to the combination of material parameters and printer capabilities used for the G-code.
Published specification: [this white paper]

Applications that use this media type: IPP 3D

Fragment identifier considerations: N/A

Additional information:

Deprecated alias names for this type: N/A
Magic number(s): N/A
File extension(s): pwgc
Macintosh file type code(s): N/A

Person & email address to contact for further information: Michael Sweet, msweet@apple.com

Intended usage: COMMON

Restrictions on usage: N/A

Author/Change controller: The Printer Working Group, c/o The IEEE Industry Standards and Technology Organization, 445 Hoes Lane, Piscataway, NJ 08854, USA

Provisional registration? (standards tree only): No
7. References


[RS274D] "Interchangeable Variable Block Data Format for Positioning, Contouring, and Contouring/Positioning Numerically Controlled Machines", EIA Standard RS-274-D, February 1979


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The authors would also like to thank the following individuals for their contributions to this white paper:

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9. Change History

9.1 July 4, 2018

- Removed old comments.
- RFC 8011 is now STD 92.

9.2 June 4, 2018

- Status: Prototype
- Type: Best Practice
- Section 3: Reword M command prohibition.
- Changed registered extension to ".pwggc".
- Added RS274NGC reference.

9.3 April 26, 2018

- Made a PWG Best Practice working draft.
- Added reference to RepRapWiki for G-Code
- Added reference to ISO 6983-1 for current official G-Code specification
- Section 4: Mention materials-col-database and materials-col-ready
- Section 4.1: Retitle as "Material Extrusion Parameters"

9.4 April 16, 2018

- Status: Interim
- Introduction: Added discussion of nozzle and filament diameter influencing portability of G-code, and why we want this.
- Added G21, M82, and M83 commands, and hooks for other printer-specific commands (safe-gcode-supported)
- Updated T command (set tool) to use 0 as the first index.
- Added sections on generating and printing safe G-code
- Added IANA registration of new attributes and the MIME media type
- Added references to 3MF slicing and RFC 8011.

9.5 April 12, 2018

Initial revision.