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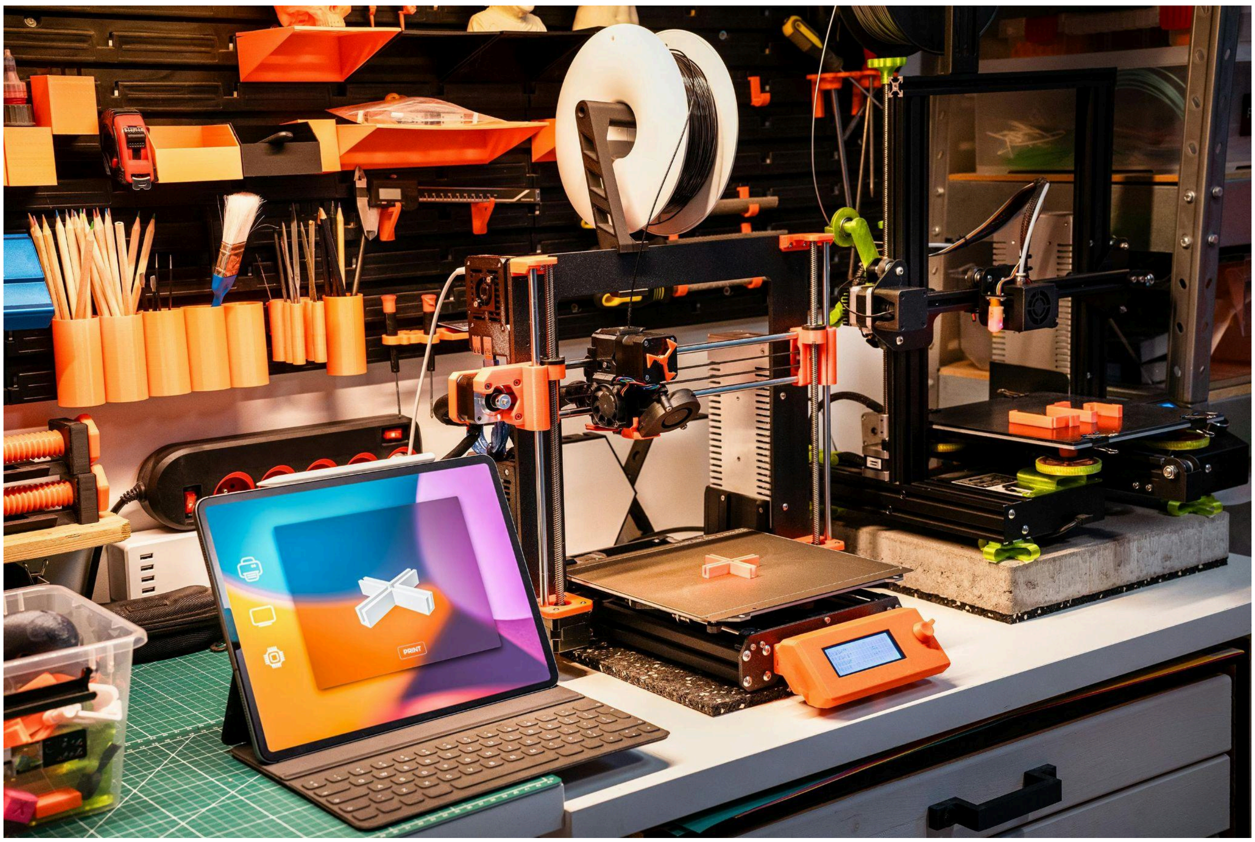
A 3-D Printable Enclosure for Millimeter-wave RADAR

An In-depth look at the pros and cons of viable candidates for best millimeter-wave performance



Abstract

Coffee. One of the most traded commodities in the world. Roasting coffee is not only an art, but science as well. For this portion of the COATL millimeter-wave radar project, our focus is to find the most suitable material to use, for our Acconeer XM125 60GHz millimeter-wave radar, to detect, with great precision, the amount of water contained in coffee beans. The following research will help to understand the types of filaments that are out on the market for 3D printing enclosure(s), to give the best results. Let's take a look at

the first point of contention in these filaments, their use cases, and which one would be best for this portion of the project.

Radar Characterization and Beam Attenuation

Radar Characterization

The XM125 radar, which includes acconeers' A121 pulsed coherent radar technology, operating at a frequency of 60GHz, but is low power in usage. Due to the nature of this project, and the aim of this report, is to find which materials, shapes, size(s), and properties, the A121, has on the proposed enclosure. By the end of this report, the final summary will include suggestions for, and against, and and all materials which would be viable candidates for the enclosure.

Since reflective materials are a hindrance to the radar beam itself, as well as any materials that attenuate the signal, the comparisons will become more obvious in the final outcomes, and conclusions.

Beam Attenuation

Beam attenuation is of great concern for this project, hence the need to understand the problem statement in detail. We must find a material that minimizes the attenuation of the beam, and its deflection, when the receiver detects, and analyzes the signal. Since signal integrity will determine the data that will be used in the measurement of the coffee beans, and the moisture content therein, we must choose wisely, the density, and thickness of the materials, in addition to the evident chemistries involved with each filament and its production quality. This is the crucial part, in the success of the enclosure, and its intended function.

Filament Material and Properties

Filament Properties

For the function of the enclosure to work as intended, we must first understand the properties of the 3D printing process itself. The outcomes of the desired design and strength of the end product play a pivotal role in the time it takes to 1) print the enclosure, and even the lid, 2) the shape of the enclosure that can be reasonably printed, and 3) the curing/drying process. The best design for the outside of the enclosure, is that of something that supports the entire enclosure, with almost no fragility in the enclosure itself, which is the backbone of the entirety of this project.

For the filament, there are so many manufacturers, and types, that it took quite a bit of time to sort out which would be best utilized, in the creation process. For the remainder of this report, we will discuss, and even review charts, which can provide a process of elimination, for each type of filament.

The ideal properties would be one which does the following: 1) not degrade over time, 2) is not soluble when it comes into contact with moisture/water, 3) is relatively cost effective, 4) has low reflectivity and is transparent to radar, and 5) maintains its structural integrity when under extreme conditions (think heat, moisture, pressure, etc…) .

Filament Material(s) Considerations and Comparisons

Looking at a couple key lines within the above chart, we can see that for price, a majority of the candidates look reasonable, and are cost effective for this project.

Now, as we look at durability, this is one of the parameters that sets these materials apart. Right off the bat, you may notice that PLA (Polylactic Acid), and Carbon Fiber Filled, are quite low with this regard. The best options in this arena are the PETG (Polyethylene Terephthalate Glycol-Modified), Nylon, and Polycarbonate, keeping in mind the price point/cost effectiveness for each of these filaments.

Moving forward to our next area is stiffness. With stiffness, this category is to see how rigid the material is after curing/cooling. For this, the worst is flexible, which is not really an issue, since this will not be considered. The best candidates for this are PLA, HIPS

(High-Impact Polystyrene), PETG, Nylon, and Polycarbonate. This is one that we will need to consider, especially when interacting with the radar beam.

Our next area of study, with regard to categories in material considerations is Ultimate Strength. The worst performers in this category are ABS (Acrylonitrile Butadiene Styrene), Flexible, and HIPS. The best performers for this category are PLA, PETG, Nylon, and Polycarbonate. Take note, these are all with an Ultimate Strength rating of 50 or greater.

Let's take a look at density, as this is one of the key components in the success of this project. Density, when we look more closely at the chart, shows us some of the materials that are not a viable option. Considering radar and the properties of the container, the lesser the density, the least susceptible to radar attenuation or absorption will be likely for the creation of the container. Higher density, has an inverse relationship to the material being transparent/"invisible" to the radar. For this project's purposes, the lowest density materials are ABS, HIPS, some Nylon, and Polypropylene. For some of the higher density materials, we have Flexible, PLA, PETG, Carbon Fiber Filled, and Polycarbonate. While we want a lower density material, we also want something that has a great rigidity profile, and stability when it comes to the elements.

Another resource for comparing materials, is found at https://www.miprotosolutions.com/post/3d-printed-material-comparison. This site does its comparisons a little bit differently, but has a similar structure to the above data that is found in the below chart (see Table 1).

Lastly, we have a couple more tables, which are similar to decision matrices, and can provide a little more insight, and guide as to the final choice, with regards to 3D printable materials. (Table 2, Table 3)

3D Printer Comparisons (Bambu Labs and Prusa Mk4S)

Achieving precise tolerances in 3D printing involves understanding both the capabilities of your printer and the characteristics of the materials you use. Below is an overview of tolerances for the Bambu Lab printers and the Prusa MK4S, along with considerations for various materials.

Bambu Lab Printers:

Dimensional Accuracy: Users have reported that Bambu Lab printers, such as the X1C, exhibit excellent dimensional accuracy. For instance, a 100 mm dimension may measure approximately 99.7 mm, indicating a minimal deviation of 0.3 mm.

Source: Bambu Labs

Design Tolerances: When designing parts, a common practice is to incorporate clearances between 0.15 mm and 0.3 mm. Specifically:

Moving Joints: 0.2–0.25 mm clearance

Glue/Screw Joints: 0.15–0.2 mm clearance

Draft/Prototype Prints: Up to 0.3 mm clearance to account for potential inaccuracies in draft settings.

Source: reddit.com

Calibration: While Bambu Lab printers are known for their accuracy, it's essential to design with appropriate tolerances to accommodate slight variations. Regular calibration and test prints can help ensure parts fit as intended.

Prusa MK4S Printer:

Precision Tolerance: A well-assembled Original Prusa printer typically achieves a precision tolerance of 0.1 mm on the Z-axis and 0.3 mm on the X and Y axes. With additional calibrations, such as extrusion multiplier adjustments and extruder linearity correction, tolerances can be refined to as little as 0.05 mm on all axes.

Source: Prusa Mk4S Printer

Design Tolerances: For part design:

Tight Fit: 0.15 mm clearance

Reasonable Fit: 0.2 mm clearance

Loose Fit: 0.3 mm clearance

These values serve as general guidelines and may require adjustment based on specific applications and materials.

Source: forum.prusa3d.com

Material Considerations: Factors such as filament diameter consistency, material shrinkage during cooling, and ambient conditions can influence print accuracy. Regular calibration and test prints are recommended to account for these variables.

Source: Print Accuracy

3D Printer Comparisons (Bambu Labs and Prusa Mk4S vs FormLabs Form2 & 3)

When comparing the Formlabs Form 2 and Form 3 resin-based 3D printers to the previously discussed Bambu Lab and Prusa MK4S filament printers, it's essential to understand the differences in printing technologies and how they impact tolerances and part accuracy.

Formlabs Form 2 vs. Form 3:

Laser Spot Size and Resolution:

Form 2: Features a laser spot size of 140 microns.

Form 3: Improved with a reduced laser spot size of 85 microns, enhancing the ability to capture finer details.

liqcreate.com

Dimensional Accuracy:

Form 2: Users have reported achieving tolerances within ±0.015 inches (±0.381 mm).

reddit.com

Form 3: Some users have observed parts being consistently oversized by approximately 0.4%, with limited options for fine-tuning the X/Y axes.

forum.formlabs.com

Support Structures and Surface Finish:

Form 3: Introduces light-touch support structures with thinner tips, making parts easier to remove and reducing surface imperfections.

liqcreate.com

User Feedback(FormLabs):

Some users have expressed a preference for the Form 2 over the Form 3, citing calibration capabilities and long-term reliability.

forum.formlabs.com

Comparison with Bambu Lab and Prusa MK4S:

Printing Technology:

Formlabs Form 2 and Form 3: Utilize Stereolithography (SLA) technology, curing liquid resin with a laser to produce parts.

Bambu Lab and Prusa MK4S: Employ Fused Deposition Modeling (FDM), extruding melted filament layer by layer.

Dimensional Accuracy and Tolerances:

SLA Printers (Formlabs): Capable of achieving high-resolution prints with fine details, but may require calibration to maintain dimensional accuracy.

FDM Printers (Bambu Lab and Prusa): Generally offer good dimensional accuracy, with tolerances typically around ±0.1 mm, depending on calibration and material used.

Material Considerations:

SLA: Offers a wide range of resins with varying mechanical properties, but parts may require post-curing and can be more brittle.

FDM: Supports a variety of thermoplastics, each with unique properties affecting shrinkage and tolerance.

Design Adjustments: Consider the specific characteristics of the chosen printing technology and material when designing parts, accounting for factors like shrinkage, support removal, and post-processing requirements.

For a visual comparison and more in-depth insights into the differences between the Formlabs Form 2 and Form 3, you might find the following video informative:

Formlabs Form 3 vs. Form 2 | See What's New

This video provides a side-by-side comparison, highlighting the advancements and changes introduced in the Form 3.

Material Summaries (Finalized list):

PLA (Polylactic Acid): A biodegradable, easy-to-print filament with high rigidity and dimensional accuracy but poor moisture resistance and radar transparency due to its density.

ABS (Acrylonitrile Butadiene Styrene): Durable, impact-resistant, and moisture-resistant, but prone to warping and moderate radar attenuation. Requires controlled printing environments.

PETG (Polyethylene Terephthalate Glycol): Combines strength, flexibility, and moisture resistance with moderate radar transparency, making it a versatile option. Prints easily compared to ABS.

Nylon: Strong, flexible, and moisture-resistant but highly hygroscopic, requiring drying before and after printing. Radar transparency varies based on density.

Resin (Formlabs SLA): High-resolution prints with smooth surfaces; moisture-resistant resins available. Radar performance depends on resin composition but typically offers high density and low transparency.

Final Summary and comparisons, with recommendation:

Recommendation for Radar Transparency > Moisture Resistance > Durability > Printability priorities (from left to right, left being highest priority):

PETG – Balanced radar performance, moisture resistance, and printability.

Nylon – Good radar transparency and moisture resistance, though printing complexity is higher.

PLA – Easy to print but moisture resistance is low and density may reduce radar performance.

ABS – Strong and moisture-resistant but radar transparency is moderate.

Resin – Precise, moisture-resistant, but potentially poor radar performance and brittle.

PETG likely provides the best tradeoff for the coffee bean XM125 radar enclosure.

Reference Charts/Tables for the above mentioned specifications:

	ABS	Flexible	PLA	HIPS	PETG	Nylon	Carbon Fiber Filled	ASA	Polycarbonate	Polypropylene	Metal Filled	Wood Filled	PVA
	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More
Compare Selected	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Ultimate Strength	40 MPa	26 - 43 MPa	65 MPa	32 MPa	53 MPa	40 - 85 MPa	45 - 48 MPa	55 MPa	72 MPa	32 MPa	20 - 30 MPa	46 MPa	78 MPa
Stiffness	5 / 10	1 / 10	7.5 / 10	10 / 10	5 / 10	5 / 10	10 / 10	5 / 10	6 / 10	4 / 10	10 / 10	8 / 10	3 / 10
Durability	8 / 10	9 / 10	4 / 10	7 / 10	8 / 10	10 / 10	3 / 10	10 / 10	10 / 10	9 / 10	4 / 10	3 / 10	7 / 10
Maximum Service Temperature	98 °C	60 - 74 °C	52 °C	100 °C	73 °C	80 - 95 °C	52 °C	95 °C	121 °C	100 °C	52 °C	52 °C	75 °C
Coefficient of Thermal Expansion	90 µm/m-°C	157 µm/m-°C	68 µm/m-°C	80 µm/m-°C	60 µm/m-°C	95 µm/m-°C	57.5 µm/m-°C	98 µm/m-°C	69 µm/m-°C	150 µm/m-°C	33.75 µm/m-°C	30.5 µm/m-°C	85 µm/m-°C
Density	1.04 g/cm^3	1.19 - 1.23 g/cm^3	1.24 g/cm^3	1.03 - 1.04 g/cm^3	1.23 g/cm^3	1.06 - 1.14 g/cm^3	1.3 g/cm^3	1.07 g/cm^3	1.2 g/cm^3	0.9 g/cm^3	2 - 4 g/cm^3	1.15 - 1.25 g/cm^3	1.23 g/cm^3
Price (per kg)	$10 - $40	$30 - $70	$10 - $40	$24 - $32	$20 - $60	$25 - $65	$30 - $80	$38 - $40	$40 - $75	$60 - $120	$50 - $120	$25 - $55	$40 - $110
Printability	8 / 10	6 / 10	9 / 10	6 / 10	9 / 10	8 / 10	8 / 10	7 / 10	6 / 10	4 / 10	7 / 10	8 / 10	5 / 10
Extruder Temperature	220 - 250 °C	225 - 245 °C	190 - 220 °C	230 - 245 °C	230 - 250 °C	220 - 270 °C	200 - 230 °C	235 - 255 °C	260 - 310 °C	220 - 250 °C	190 - 220 °C	190 - 220 °C	185 - 200 °C
Bed temperature	95 - 110 °C	45 - 60 °C	45 - 60 °C	100 - 115 °C	75 - 90 °C	70 - 90 °C	45 - 60 °C	90 - 110 °C	80 - 120 °C	85 - 100 °C	45 - 60 °C	45 - 60 °C	45 - 60 °C
Heated Bed	Required	Optional	Optional	Required	Required	Required	Optional	Required	Required	Required	Optional	Optional	Required
Recommended Build Surfaces	Kapton Tape, ABS Slurry	PEI, Painter's Tape	Painter's Tape, Glue Stick, Glass Plate, PEI	Glass Plate, Glue Stick, Kapton Tape	Glue Stick, Painter's Tape	Glue Stick, PEI	Painter's Tape, Glue Stick, Glass Plate, PEI	Glue Stick, PEI	PEI, Commercial Adhesive, Glue Stick	Packing Tape, Polypropylene Sheet	Painter's Tape, Glue Stick, PEI	Painter's Tape, Glue Stick, PEI	PEI, Painter's Tape
Other Hardware Requirements	Heated Bed, Enclosure Recommended	Part Cooling Fan	Part Cooling Fan	Heated Bed, Enclosure Recommended	Heated Bed, Part Cooling Fan	Heated Bed, Enclosure Recommended, May Require All Metal Hotend	Part Cooling Fan	Heated Bed	Heated Bed, Enclosure Recommended, All Metal Hotend	Heated Bed, Enclosure Recommended, Part Cooling Fan	Wear Resistant or Stainless Steel Nozzle, Part Cooling Fan	Part Cooling Fan	Heated Bed, Part Cooling Fan

Table 1 *Comparison of FDM and SLA Printing Materials*

Category	SLA Resin	PETG (Best FDM Choice)	Polycarbonate (PC)	Polypropylene (PP)
Moisture Resistance	✅ Excellent	✅ Excellent	✅ Excellent	✅ Excellent
Durability	⛔ Brittle (unless tough resin)	✅ Good	✅✅ High	⛔ Moderate
Printability	✅✅ Very High Precision	✅✅ Easy	⛔ Hard (warping issues)	⛔ Hard (adhesion issues)
Density (g/cm^3)	🔹 ~1.1 - 1.2	🔹 1.23	🔹 1.2	🔹 0.9
Radar Transparency	⛔ Uncertain (may absorb waves)	✅ Likely Good	⛔ May Block Signals	✅ Likely Best

Table 2 *Best Candidates of FDM and SLA Printing Materials - Best Candidates Side-by-side*

Material	Density (g/cm³)	Considerations for Radar & Structure
Polycarbonate (PC)	1.2	Strong and durable but could interfere with mmWave signals.
PETG	1.23	Good strength, moderate density, and likely decent radar transparency.
PLA	1.24	Easy to print but may absorb moisture and is not ideal for long-term use.
ABS	1.04	Good strength but less radar transparent. Requires an enclosure when printing.
Nylon	1.06 - 1.14	Durable but absorbs moisture over time, which could alter its properties.
Polypropylene (PP)	0.9	Least dense, great for radar transparency, but difficult to print reliably.

Table 3 *Best Candidates of FDM and SLA Printing Materials - Density*