nature portfolio

Peer Review File

Overprinting with Tomographic Volumetric Additive Manufacturing

Corresponding Author: Mr Felix Wechsler

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This manuscript focuses on significant improvements to Tomographic Volumetric Additive Manufacturing (TVAM). In particular, it demonstrates two important advancements: (1) printing in a rotating square cuvette, and (2) effective printing around and on objects embedded in the print volume. The fundamental enabler for these advancements is their open source framework for differentiable physically-based ray optical analysis of the 3D print volume (including pre-existing objects) and corresponding rapid calculation of the necessary tomographic projections required to print the desired structures. Given the significance of the authors results and methods, I recommend acceptance for publication pending addressing the following comments.

Questions/comments:

1. My main confusion in reading the manuscript was caused by the lack of definition of "overprinting". It was only when I read Section 3 that it became clear that the authors mean printing such that the printed structure adheres to, is attached to, or accommodates objects that already exist in the 3D print volume. This definition needs to be made at least in the introduction. Given that "overprinting" is used in the title as well as the abstract and the introduction, it is important that the reader understands as soon as possible what the authors mean.

2. Particularly helpful or well-done aspects of the manuscript:
- Nice review of previous TVAM work to place the manuscript's results in context.
- Intensity histograms of object and void voxels are a very effective way to represent relative voxel exposures.
- Being able to use a square cuvette is especially useful.
- Sect. 2.3 comparison of absorptive and reflective rod assumptions is effective.

3. When looking at intensity histograms, many void voxels receive a dose that is 80-85% of the maximum normalized dose. How does the relatively small difference between object and void voxel dose result in polymerized and unpolymerized material, respectively? There is no discussion of inhibitors added to the resins, which is presumably how this his accomplished, or what the considerations are for setting inhibitor concentration.

4. Intersection over Union (IoU) score: how does the chosen threshold that gives a high numerical score relate to the actual photopolymerization threshold?

5. Last paragraph of Sect. 2.4: "The print required over-polymerization to ensure structural stability..." How much additional exposure was required? 5%? 50%?

6. Figure issues:
- Color bar for Figs. 1d,1e,1f needs to be larger so it is visible.
- Fig. 2e and 2f are too small, also 2c.
- Figs. 4b, 5b - Why does the normalized dose go >1?

(Remarks on code availability)
The code is clear and complete.

Reviewer #2

(Remarks to the Author)
Review of “Overprinting with Tomographic Additive Manufacturing”

This manuscript reports an advance in a technique called “overprinting” that is used in the context of volumetric additive manufacturing. The key advance here is that the authors have incorporated a ray tracing pipeline into the projection computation to deal with refractive and reflective objects in the print region.

General comments:
- I found that the experiments less compelling at the end of the paper. In particular, I would strongly suggest to remove sections 2.4 and 2.5.
- In my opinion the raytracing method is more powerful than the authors demonstrate.
- I would encourage the authors to resubmit a substantially revised manuscript with the final two experiments removed. Instead, I think that a demonstration of an overprint where the object(s) inside are refractive AND reflective (perhaps spatially varying, or there are multiple objects, some refractive and some reflective) would be the ultimate demonstration of the power of this technique. Furthermore, if the authors could demonstrate that a print really does (functionally) fail when ignoring the occlusion or the optical properties of the object, that would be much better. For example, the gear in Fig. 3d and i are barely different and I suspect both would work in any application. It’s not even clear that the hole that is supposedly overexposed is actually the incorrect size because the authors have not disclosed the designed model dimensions.

Specific comments. Please include line numbers for subsequent submissions.

- Abstract is too long. Suggest cutting to half the length and avoid going into detail on each experiment.
- The Authors must define “overprinting” in the abstract if they want to use the term in the title.
- Some content in introduction doesn’t seem relevant, such as the discussion on striations? This is a very minor and peripheral issue in the paper.
- “Due to rotation of the vial, overprinting of existing structures…” Need to define overprinting. Should also define it in the abstract since it is in the title and not common knowledge.
- Suggest removing some discussion in introduction as it is very long
- In Fig. 1 the laser VAM setup is introduced. There is lots of good optical information in 4.1.1 about this system, but the depth of field is not stated. This is potentially quite important given the small pixel size.
- For Fig. 1 it is easy to miss that this is done in a square vial. Perhaps the authors may want to emphasize this a bit more by explicitly stating that this is non-standard for VAM (typically using cylindrical vials).
- In Fig. 1a, need arrows on the rays to indicate direction of propagation
- What is the refractive index of the polystyrene and the resin? How accurately does this need to be known for printing to work well?
- “which is close to the maximum”… do the authors mean close to 1? Better to state this explicitly, otherwise reader might wonder if there is another reason for a different maximal value. I also suggest a reference here to provide better context to the histogram plot.
- Indicate on Fig. 1b where the threshold is that gives the quoted IoU score.
- Colorbar of Fig. 1c needs label and units. Also, in my opinion “dose slice” is more appropriate than “intensity slice” here.
- Top of p.5: “the optimization restricts light from passing through the corners”. How close to the corners is light allowed to pass? How is the size of this corner region chosen?
- How is the square cuvette mounted so that it’s orientation corresponds correctly to the calculated projections? Is this done by hand? How accurate do the authors expect to be?
- What is the design with of the channels printed in Fig. 1? I see this is in methods. I strongly suggest to put this detail in the main text.
- From the pictures it looks like the alignment between the channel and the nozzle is quite good. I strongly urge the authors to quantify and report the alignment accuracy, even just based on the photographs presented.
- Fig2: How are the glass spheres positioned in place? Is the resin viscosity so high that they don’t move? Are they density matched to the resin? I see this is in the methods. Please either refer the reader here or put it in the main body.
- “the quality of the optical simulation was reduced…” Reduced from what to what? Could the authors please specify how they quantify the simulation quality and the original vs. reduced quality parameters? I see this is in the methods. Please either refer the reader here or put it in the main body.
- I don’t find the intensity histograms to be very insightful. I would recommend to put in the supplementary.
- In fig. 2 f, it looks like the channel is not as well aligned with the nozzles as in Fig. 1: there is some blue around the nozzles. What does the design look like at the nozzle? Does the channel encircle the nozzle, or is it inside the nozzle? I think it would be valuable to have a CAD rendering or depiction of the channel design in all cases.
- Fig. 2d: Which slices are these? Does the second one include the nozzle, or is it a refractive sphere? It would make sense to indicate the position of these slices with a depiction of the design, or in the photographs on Fig. 2b. Otherwise the reader is left to guess at the identity of the features in Fig.2d.
- The start shaped high dose (suggest changing intensity to dose again here) in Fig. 2d is curious. I suppose this is an artifact of the square chamber? Were similar bright regions occurring in Fig. 1? Could these be eliminated or reduced using a different optimization approach (perhaps a different loss function) or is this a fundamental result of dose application in a square cuvette?
- Scale bar is required for all insets in this paper (eg. Fig. 2f, 1i,g,h)

- Here the inner diameter of the channels is designed to be 0.7mm. What is the fabricated diameter? The authors should check this experimentally.
- Fig. 3: again, I don't think the histogram adds any insight. The histogram improvement looks marginal, but from the intensity (dose) slices one can immediately see the value.
- For the reflective rod experiment, it would be interesting to have a supplementary figure showing a slice of the simulated intensity resulting from illuminating the rod with a uniform intensity from one direction. This would give the reader a graphical understanding of how the rod is modelled.
- How did the Authors arrive at the parameter alpha=0.04 used for the Beckmann distribution for the rod? This seems important – an incorrect alpha value might even be worse than the non-reflective model.
- I think it would be useful to elaborate a bit more on the optical model of the rod, since printing over a reflective object is a major point of novelty of this paper. Does the Beckmann distribution's alpha parameter determine the overall amount of light reflection? Does it determine the angular spread of reflected light? I see there is a reference, but I think it would be very helpful for the reader to distill and convey the essence of this model in the main body of the manuscript.
- There is no discussion of the adhesion of the gear on the rod. For example, if someone were to push on the gear lightly, does it stay on the rod? This is an import aconsideration for overprinting. Perhaps the authors could show a video that qualitatively demonstrates the adhesion strength?
- "By selecting the optimal threshold, we achieved a high fidelity print with IoU…" This should be changed to something like "This optimized projection set reaches a simulated IoU of…". The IoU here is not measured from the actual print, but instead from the simulated dose.
- Fig 4: The geometry of this experiment is really not clear. How is the LED placed in the vial and what does it look like? Its size? It would help to have a photograph of just the LED, potentially in its mount, to understand what is going on here. Or perhaps a CAD drawing.
- Fig 4a: I really don't think this is necessary in the main body – I would suggest to move to supplementary.
- Fig. 4c: indicate where this slice is taken in the 3D rendering in Fig. 4e.
- For this experiment, what is the design focal length or surface radii of the fabricated lens? Is the fabricated lens close to the design? How far away is the screen in Fig. 4g? Is the image supposed to be created at a particular distance from the lens? There is a lot of information missing in this section.
- From the pattern is Fig. 4d, it's not clear that the occlusion of the LED is making any difference to the projections. I would expect to see a darker region indicating the LED at the top, but I don't see any. Could the authors outline the region where the LED is located in Fig. 4g?
- Colorbars in this figure are all missing labels and units.
- The authors mention that this print required overpolymerization. How are the authors determining when to terminate the print? Was it trial and error? It would seem that this is a design or optimization issue. Eitther the design should be modified so the pillars are thicker or the optimizer is not actually converging on a uniform dose everywhere.
- Fig. 5: Again I don't think Fig. 5a is required here, and in this figure, the DMD is not visible so the meaning of the red and blue rays is not clear without looking at Fig. 4 and inferring.
- I don't really find this experiment very compelling. The image in Fig. 5g is very hard to interpret. I would suggest removing this experiment from the paper as the previous experiments in the manuscript are better examples of this technique.
- "Notably, LEDTVAM setups are not possible to simulate with other existing software solutions." I disagree with this statement. All of the previous TVAM papers that use LEDs do simulate dose to some degree of accuracy. In particular Daniel Webber et al., "Versatile volumetric additive manufacturing with 3D ray tracing," Opt. Express 2023 does something very similar to the technique in this paper, however, it is not used for overprinting. I suggest to modify this statement to be more clear that the authors are referring to overprinting and not TVAM in general.
- "Furthermore, our overprinting approach enables the direct fabrication of microfluidic biomimetic channels without the need for additional post-processing or assembly steps, thereby minimizing the risk of contamination and mechanical damage. To our knowledge, this is the first time this has been demonstrated with TVAM based methods.". I this this is a great result in the paper. However, it is not the first such demonstration: https://readily3d.com/wp-content/uploads/2025-05-20-PR-On-chip-printing.pdf.
- I think it is a bit of a stretch to say that the channels printed in this paper are "vascular-like". They need to be significantly more complex to approach vascular networks.
- "By incorporating the lens at an appropriate distance from the LED, the system effectively reimages the printed pattern onto the screen, illustrating the potential to integrate arbitrary projection functionalities directly onto compact light sources." There is no indication in the manuscript that there is a particular distance for the screen, not that the lens is designed in such a way to re-image the cross at a particular distance.
- "Since LED-based setups are not yet common in the literature, we aim to provide a more detailed de scription. The general configuration can be observed in Figure 6a." This is a curious statement since the first peer reviewed published system (Kelly et al. Science 2019) is an LED system, and there have been many since by the CU Boulder and NRC teams to name a few.
- Section 4.7. What is the rationale for the changes in the projected power? One would expect to keep the power the same for each system (laser and LED), but her it seems to be changed randomly. Also, why is the rotation rate changed among the various prints? 47 deg/s is particularly strange.

(Remarks on code availability)
It is more appropriate to review the software at a later date when paper has been significantly revised.

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)
This impressive work significantly advances the state of the art in overprinting, whereby photopolymer objects are printed around pre-existing solid structures via specially designed, tomographically reconstructed light patterns. Two key research challenges in this area have been to design projection patterns for specific embedded objects whose positions may exhibit some variability or deviation from intended positions (so-called “context-aware” printing), and also to compensate for reflection or scattering (rather than just absorption) by embedded objects. This manuscript makes significant progress on both challenges.

The result showing the importance of including reflection/scattering when overprinting onto a shiny cylinder are impressive: compared to assuming the shaft to be absorptive, the printing quality is significantly improved. This is an important result for many potential manufacturing applications.

The description of the engineering of the LED-based (as opposed to laser diode-based) system is also a valuable contribution.

I just have one question/comment:

Section 2.2. The work on context-aware printing around silica spheres is impressive and valuable. I am not convinced though that the term “on-the-fly” accurately reflects what was done. The authors used imaging to determine the positions of embedded spheres, then calculated printing patterns. While done impressively quickly (30 s) this was not, to my mind, done “on the fly” in the sense of computation being done at the same time as printing. Therefore the computational speed is a significant advantage but not an integral attribute of the process methodology (i.e. slow computation would be possible; one would just have to wait longer between imaging and printing). Could the authors please clarify this point?

(Remarks on code availability)

Reviewer #5

(Remarks to the Author)
Summary:
The study demonstrates the successful overprinting of different shapes for different applications using Tomographic Volumetric Additive Manufacturing (TVAM) method. For this purpose, the newly developed light pattern generation algorithm, Dr.TVAM, with the capability of accounting for the occlusions and changes of the refraction indices in the light propagation, has been used. The authors have reported successful overprints for different applications including bio-applications and optics, while using both laser and LED light sources.
While the overprinting examples are more advanced compared to the ones mentioned in the literature and the examples show the capabilities of the light pattern generator algorithm that is suggested by the authors, the concept of overprinting as well as printing in vials with non-circular cross-sections have already been documented in the literature, and accordingly the study does not represent a significant novelty. Nonetheless, the authors are recommended to address the following points in the manuscript.

1- In all the histograms that are presented in this paper, there is a huge overlap between the object and void voxels. It has been shown and discussed in the literature that a gap between the two can improve the quality of the prints and help to prevent the undesired under- and over-curing. It is necessary that the authors explain and discuss the reason for this overlap and discuss how it affects the print quality. Additionally, why is the normalized dose of the histograms higher than 1.0? How are the dose values normalized?

2- In the printing patterns shown in Fig. 2e, the in-part regions or object voxels, are darker than the surrounding medium around them. This seems counterintuitive, as the in-part regions should receive a higher dose and accordingly look brighter in the light patterns. Some explanation in this regard can improve the understanding of this figure.

3- It is mentioned that the overprinting process in the context-aware perfusion system (section 2.2) takes around 3 minutes to complete (from taking the images to completing the print). How is the vertical movement of the silica beads, namely the movement due to gravity and other forces (buoyancy and local drag forces due to the convective effects induced by exothermic reactions), controlled or taken into account?

4- In Fig. 4, there is a considerable difference between the 3D rendering and the printed part. Authors have mentioned that

LED-printing leads to lower accuracy compared to laser printing. However, the convex surface of the lens (Fig. 4e) is observed to be printed as a concave surface (Fig. 4f), which is quite a considerable difference. It is important that the authors clarify on the reasons behind this issue and argue when the low-accuracy prints of LED-based printing can be useful. Regarding the striations, Rackson et al suggested a method to mitigate this issue for laser printing. Why didn't the authors use that methodology to tackle the striation challenge for higher surface qualities.
Additionally, the LED-based print represented in Fig. 5 seems to have a higher quality, though the authors have not put any image of the rendered geometry. It would be nice if the authors made a comparison between the STL files that have been used for the printing and the final prints to show the fidelity of the prints.

5- In the Discussion section, the authors claimed that the overprinting of microfluidic channels did not require any post-processing stage. Why did not this or other prints in this study require a post-curing stage, where the partially cured parts are exposed to prolonged UV exposure?

6- Minor comment: In the last line of the first paragraph of the Introduction section, the word "exceeds" is repeated.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This authors have done a good job addressing reviewer comments and the paper is now suitable for publication. Typo note: In Section E of the SI the figure number used is "8" and it should be "10". I applaud keeping the dose histograms in the SI rather than deleting them as suggested by another reviewer. I found them to be particularly useful.

(Remarks on code availability)
The code is clear and complete.

Reviewer #2

(Remarks to the Author)
I commend the authors for making many improvements in the paper.

However, I cannot yet recommend this paper for publication for one main reason: the authors have still not experimentally demonstrated improved results with reflective objects that could not have likely happened by other means (namely over or under exposure).

For this, the authors present Section 2.3 "Gear on Metal Rod". Here a gear is overprinted onto a reflective metal rod. However, as I said in the initial review, there is little in the result of Fig. 3c/g to show that the reflection-corrected light patterns make any difference to the print. The authors show that with the uncorrected patterns, the hole is 0.71mm in diameter and with the corrected patterns, the hole is 0.96mm. There are several issues with this:

1. These measurements are made from an oblique angle, and for the 0.71mm hole, it appears that the authors are measuring from the left side on top of the hole to the right side on the bottom of the hole. By my measurement of the image, the true diameter of the hole is a bit larger, about 0.84mm. This is less than the design value (0.90mm) by the same amount as the scattering corrected print is too large (+/- 0.06mm), which is 0.96mm. The difference in print dimensions is actually very small, and equally erroneous on both prints. Furthermore, there is no error provided on the measurement of the hole diameter. There is more than one hole in the gear. Why not measure all of them and take the mean +/- standard deviation? One should also measure whether there is a difference in the hole diameter along different orientations. Is the hole truly circular? All of this gets at the following point: the hole is slightly off from the design value… is this difference in hole dimension between scattering and no scattering correction statistically significant or not and does it necessarily stem from the scattering or could it have happened due to global exposure differences?

2. How do we know the difference in size isn't simply because of slight over or under exposure? At these length scales (+/- 60um), VAM is very sensitive to exposure time. The authors should show that this difference is repeatable, and not just the result of two prints with manually controlled exposure times. I actually do believe that the scattering correction is making a difference here, but for a paper in Nature Comms, I would expect to have a more compelling dataset for the most definitive and novel part of the paper. One possible route is the following: measure the size of the gear teeth (positive feature) and holes (negative) for different exposure times. If the scattering correction is working as intended, the teeth and holes should either underexposed (teeth too small, hole too big) or overexposed (teeth too big, hole too small). If scattering correction is not compensating properly, then there will be an exposure time that leads to the teeth being too small (under exposed) and holes being too small (over exposed). For the current data in Fig. 3, which situation do we have? One could consider also

printing both corrected and uncorrected gears onto the same rod in the same print for comparison. I encourage the authors to come up with an improved test print geometry to unequivocally show that the scattering correction enables printing of an object that is not otherwise possible in the presence of reflection/scattering.

3. The reason why I belabour #2 above is because the stated method for estimating the only reflection/scattering parameter (alpha) is “we assumed a value of alpha = 0.04 which was visually matched to comparison renderings”. This approach is fraught with issues: it is qualitative, it depends on the monitor and rendering software. Does the lighting in real life match that in the rendering? Would different observers estimate different alpha values? And so on… This is the sole extra parameter responsible for calculation of the scattering effect on the patterns, yet it is not even known/estimated quantitatively. And so therefore, even if it is helping to improve the overprint quality, it is some sense accidental that the correction is not over or under correcting.

For this reason I strongly encourage the authors to measure some aspect of the reflection and match it to a Beckmann distribution. For example, perhaps the relative intensity at a few different reflected angles could be measured experimentally and then a Beckmann distribution could be fitted to the result. It need not be a complex measurement, and would add significant weight to the claim that this model and the associated corrections are accurately correcting the projections.

I am impressed with the new supplementary section B Dice on Mirror. In the reflection-aware case, the dice is no longer connected to the mirror, Is that correct? If so, perhaps the authors could image it more clearly on a different background with more contrast? I am a little surprised that the simulation/print comes out mostly OK when the mirrors are assumed to be absorbing and non-reflecting.

Final comment on Fig. 4. Could the authors improve the imaging of the cross (Fig. 4g)? Perhaps the projected image could be demagnified and projected onto a camera sensor. I suggest to refrain from vague scale bars (“around 10cm”) and instead use an imaging arrangement where scalebars can be properly known.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)
My earlier comment has been satisfactorily addressed.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The authors have addressed all of my comments. The new Figures 3, 9, 11 are very clear and provide good quantitative evidence for the author's claims. I commend the authors for these improvements.

In my opinion, the paper is now ready for acceptance in Nature Communications.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

(Remarks on code availability)

Response to rewiever's comments

In the following, we would like to response to the reviewers' comments. We made significant changes to the manuscript to include the suggestions.
In general, all changes in the manuscript are indicated by the following color codes:

- Added text looks like this
- ~~Replaced text~~looks like this
- ~~Removed text looks like this~~

All new configuration and mesh files are currently available over: https://go.epfl.ch/overprinting_revisions

1 Replies to the reviewers

In the following we reply to all reviewer comments in red color.

2 Reviewer #1 (Remarks to the Author)

This manuscript focuses on significant improvements to Tomographic Volumetric Additive Manufacturing (TVAM). In particular, it demonstrates two important advancements: (1) printing in a rotating square cuvette, and (2) effective printing around and on objects embedded in the print volume. The fundamental enabler for these advancements is their open source framework for differentiable physically-based ray optical analysis of the 3D print volume (including pre-existing objects) and corresponding rapid calculation of the necessary tomographic projections required to print the desired structures. Given the significance of the authors results and methods, I recommend acceptance for publication pending addressing the following comments.
Questions/comments:
1. My main confusion in reading the manuscript was caused by the lack of definition of "overprinting". It was only when I read Section 3 that it became clear that the authors mean printing such that the printed structure adheres to, is attached to, or accommodates objects that already exist in the 3D print volume. This definition needs to be made at least in the introduction. Given that "overprinting" is used in the title as well as the abstract and the introduction, it is important that the reader understands as soon as possible what the authors mean.

> ⇒ We added a definition in the abstract and the main text.

2. Particularly helpful or well-done aspects of the manuscript:

- *Nice review of previous TVAM work to place the manuscript's results in context.*
- *Intensity histograms of object and void voxels are a very effective way to represent relative voxel exposures.*
- *Being able to use a square cuvette is especially useful.*
- *Sect. 2.3 comparison of absorptive and reflective rod assumptions is effective.*

3. When looking at intensity histograms, many void voxels receive a dose that is 80-85% of the maximum normalized dose. How does the relatively small difference between object and void voxel dose result in polymerized and unpolymerized material, respectively?

⇒ Please note that the histogram is in a logarithmic scale so the absolute number of voxels is relatively low. For example for Figure 1, the IoU is 0.9972 so the overlap is less than 0.3 %.

There is no discussion of inhibitors added to the resins, which is presumably how this his accomplished, or what the considerations are for setting inhibitor concentration.

⇒ For acrylate and methacrylate-based photoresins, as the ones used in this study, oxygen naturally acts as inhibitor. Hence, we did not need to add additional inhibitors to attain the feature sizes presented here. We add in the manuscript: We do not add any inhibitor except oxygen which is naturally dissolved into the resin during mixing.

4. Intersection over Union (IoU) score: how does the chosen threshold that gives a high numerical score relate to the actual photopolymerization threshold?

⇒ The numerical threshold is a relative, dimensionless dose. In practice, exposure time and power need to be tuned to obtain the desired print quality. We do not have access to the value as it is a dimensionless (relative) quantity. The real absorbed energy can be only estimated from the absorbance of the photoinitiator and the projected intensity.

5. Last paragraph of Sect. 2.4: "The print required over-polymerization to ensure structural stability..." How much additional exposure was required? 5%? 50%?

⇒ We added a new experiment, please see Figure 4. By using an improved 3D model and a more accurate refractive index for the LED, we achieved a better and more stable print without needing to rely on overexposure to secure it to the LED.

6. Figure issues: - Color bar for Figs. 1d,1e,1f needs to be larger so it is visible. - Fig. 2e and 2f are too small, also 2c.

⇒ We increased the size for better visibility.

- Figs. 4b, 5b - Why does the normalized dose go > 1?

⇒ Thank you for pointing out this mistake. In fact,*normalized dose* was the wrong term. In simulation it is a dimensionless dose. We force the dose of the void regions to stay below a given lower threshold T_L, and the dose of the objects regions stay above a given upper threshold T_U, but also constrained to be below 1 in the loss function. The final loss value is numerically not 0, so some of the dose can be above 1. We removed the term *normalized dose* and replaced it by *simulated dose*.

3 Reviewer #1 (Remarks on code availability)

The code is clear and complete.

4 Reviewer #2 (Remarks to the Author)

Review of "Overprinting with Tomographic Additive Manufacturing"
This manuscript reports an advance in a technique called "overprinting" that is used in the context of volumetric additive manufacturing. The key advance here is that the authors have incorporated a ray tracing pipeline into the projection computation to deal with refractive and reflective objects in the print region.
General comments: - I found that the experiments less compelling at the end of the paper. In particular, I would strongly suggest to remove sections 2.4 and 2.5.

⇒ We appreciate your remark. We improved the quality of section 2.4 and moved the microlens prints (section 2.5) to the supplementary material.

- In my opinion the raytracing method is more powerful than the authors demonstrate.

⇒ We believe the reported examples, along with an additional demonstration involving printing in a square container with two reflective surfaces, sufficiently showcase the strength of our approach. Optimizing projection patterns without considering square geometries and/or reflective surfaces would results in fundamentally wrong or significantly worse prints. This new experiment is attached in the supplementary materials.

- I would encourage the authors to resubmit a substantially revised manuscript with the final two experiments removed.

⇒ We improved the quality of the first experiment and moved the second experiment to the supplementary material.

Instead, I think that a demonstration of an overprint where the object(s) inside are refractive AND reflective (perhaps spatially varying, or there are multiple objects, some refractive and some reflective) would be the ultimate demonstration of the power of this technique.

⇒ In fact, our overprinting gear example already contains non-trivial refraction and reflection parts. The entire ray-path through (air → cuvette → resin → diffuse gear reflection → resin → potentially total internal reflection → . . .) contains both reflection, absorption and refraction. But we appreciate your comment and conducted another experiment with two fully reflecting mirrors inside the cuvette. We successfully printed a dice onto the surface of one mirror. Notably, these mirrors have also a glass layer which we had to consider, thus including an additional level of both refraction and reflection. Not taking into account all these aspects leads to evident print failure close to the reflective surfaces. The results are added in the supplementary (Figure 7).

⇒ Light propagation through a spatially varying refractive index is possible to simulate via the Eikonal equation. However, this requires significant algorithmic engineering and experimental verification. This is beyond the scope of this work.

Furthermore, if the authors could demonstrate that a print really does (functionally) fail when ignoring the occlusion or the optical properties of the object, that would be much better.

For example, the gear in Fig. 3d and i are barely different and I suspect both would work in any application. It's not even clear that the hole that is supposedly overexposed is actually the incorrect size because the authors have not disclosed the designed model

⇒ Although not explicitly mentioned in the main text, the hole diameter is indicated to be 0.9 mm (see Figure 3f). Further, we have disclosed all model design files online in the provided GitHub link. In the case of the gear example, as proven both in simulation and experiment, fine features close to the metal rod such as the holes are not correctly printed if the optical properties of the object are not taken into account (around 20% deviation). We believe that this example, together with the new Figure 7, provide enough proof that Dr. TVAM critically improves print quality in challenging overprinting scenarios.

Specific comments. Please include line numbers for subsequent submissions.
- Abstract is too long. Suggest cutting to half the length and avoid going into detail on each experiment. - The Authors must define "overprinting" in the abstract if they want to use the term in the title.

⇒ We agree to both comments and reduced the length and added a concise definition.

- Some content in introduction doesn't seem relevant, such as the discussion on striations? This is a very minor and peripheral issue in the paper.

⇒ We argue that striations are critical artifacts when it comes to lens printing applications where smooth surfaces are desired. As discussed in the manuscript, this motivates the use of an LED-based TVAM setup to mitigate such effects. We therefore find the discussion over striation critical for the reader to fully understand our study and overall to have a better understanding of the field.

- "Due to rotation of the vial, overprinting of existing structures..." Need to define overprinting. Should also define it in the abstract since it is in the title and not common knowledge.

⇒ We agree and defined overprinting in the abstract and main text.

- Suggest removing some discussion in introduction as it is very long

⇒ We appreciate the suggestion. However, because our work spans several aspects of 3D printing and TVAM, we believe that providing the necessary background will help the broader community better understand the contributions of this study.

- In Fig. 1 the laser VAM setup is introduced. There is lots of good optical information in 4.1.1 about this system, but the depth of field is not stated. This is potentially quite important given the small pixel size.

⇒ The depth of field is around 25 mm assuming a beam waist half the pixel size in printing space. This estimation has been added in the manuscript.

- For Fig. 1 it is easy to miss that this is done in a square vial. Perhaps the authors may want to emphasize this a bit more by explicitly stating that this is non-standard for VAM (typically using cylindrical vials).

⇒ We made it more clear and added: In TVAM typically round vials are used to contain the resin but since our framework is very general, arbitrary container shapes are possible.

- In Fig. 1a, need arrows on the rays to indicate direction of propagation

⇒ We added arrows to make it clearer.

- *What is the refractive index of the polystyrene and the resin? How accurately does this need to be known for printing to work well?*

⇒ The values are of the polystyrene cuvette is $n = 1.54$ (database value), the Gel-MA resin is $n = 1.3512$ and $n = 1.4849$ for the acrylate resin as stated in the manuscript. We use an optical refractometer to determine the value of the resin refractive index. TVAM is relatively robust with respect to variations of the refractive index of the cuvette. More detrimental are deviations in the resin refractive index. It can be estimated from geometrical refraction that, for a 10 mm vial, the error in the maximum ray displacement is approximately $\frac{\Delta n}{n} \cdot 10\,\mathrm{mm}$ where Δn is the refractive index error. For $\Delta n = 0.001$ and $n = 1.4847$ the displacement error is around 7 µm which is well below the printing accuracy.

- *"which is close to the maximum"... do the authors mean close to 1? Better to state this explicitly, otherwise reader might wonder if there is another reason for a different maximal value. I also suggest a reference here to provide better context to the histogram plot.*

⇒ We added another clarifying sentence to the manuscript and a reference to Rackson et al. which introduced histogram plots prominently. We added in the manuscript: Histograms plots are an effective way to judge if there is a good separation between void and object exposure [6].

- *Indicate on Fig. 1b where the threshold is that gives the quoted IoU score.*

⇒ We added a red dashed line to the histogram plot to make it clear.

- *Colorbar of Fig. 1c needs label and units. Also, in my opinion "dose slice" is more appropriate than "intensity slice" here.*

⇒ We believe the figure has already labels on the colorbar. Since we use dimensionless intensities in simulation, there is no unit associated with it. We changed all occurrences of *intensity slice* to *dose slice*.

- *Top of p.5: "the optimization restricts light from passing through the corners". How close to the corners is light allowed to pass? How is the size of this corner region chosen?*

⇒ We measured the frosted regions of our cuvettes to be of length 0.9 mm on each side. Consequently, we filter out a region within a radius of 0.9 mm to the corner. This value is also available in our provided configuration files.

- *How is the square cuvette mounted so that it's orientation corresponds correctly to the calculated projections? Is this done by hand? How accurate do the authors expect to be?*

⇒ Yes, it is hand mounted. The orientation is aligned with a red laser reflected on the vial surface and referenced to the back reflection of the printing laser. The angular accuracy is estimated to be around $\pm 0.5°$. The vertical alignment is monitored with a camera behind the printing system and in the order of ± 100 µm.

- *What is the design with of the channels printed in Fig. 1? I see this is in methods. I strongly suggest to put this detail in the main text.*

⇒ Yes it was mentioned in the methods section but we added a sentence in the main text to make it clear. On GitHub we also provide direct access to the 3D mesh files with all details. We also add 3D renderings of all structures in the supplementary.

- From the pictures it looks like the alignment between the channel and the nozzle is quite good. I strongly urge the authors to quantify and report the alignment accuracy, even just based on the photographs presented.

⇒ We added the following sentence to the methods section: We estimate the vertical precision to be around 100 µm.

- Fig2: How are the glass spheres positioned in place? Is the resin viscosity so high that they don't move? Are they density matched to the resin? I see this is in the methods. Please either refer the reader here or put it in the main body.

⇒ Gel-MA thermally gels when cooled down. As stated in the method section, we partially filled the cuvette with warm photoresin and then let it gel in a fridge. Then, a first sphere was placed and more warm photoresin was added, which was then again cooled down at 4C. We repeated this step to include a second sphere. This procedure is described in the manuscript in section 4.4.2 and we added another reference from the main text to the methods section.

- "the quality of the optical simulation was reduced..." Reduced from what to what? Could the authors please specify how they quantify the simulation quality and the original vs. reduced quality parameters? I see this is in the methods. Please either refer the reader here or put it in the main body.

⇒ Indeed, this is explained in the methods section. We added a reference to the details in the methods section. We would like to highlight that all configuration files and source code are publicly available.

- I don't find the intensity histograms to be very insightful. I would recommend to put in the supplementary.

⇒ Yes, we agree. We left an histogram in Figure 1 as an example but further histograms were moved to the supplementary.

- In fig. 2 f, it looks like the channel is not as well aligned with the nozzles as in Fig. 1: there is some blue around the nozzles. What does the design look like at the nozzle? Does the channel encircle the nozzle, or is it inside the nozzle? I think it would be valuable to have a CAD rendering or depiction of the channel design in all cases.

⇒ Yes, in this example, we could observe some leakage. This is most likely due to small (1-3 pixels / tens of micrometers) mismatch in the alignment process. Further, since Gel-MA is a relatively soft and porous material, the water soluble dye can easily diffuse through the structure and small gaps. As suggested, we added renderings of all example into the (Figure 10).

- Fig. 2d: Which slices are these? Does the second one include the nozzle, or is it a refractive sphere? It would make sense to indicate the position of these slices with a depiction of the design, or in the photographs on Fig. 2b. Otherwise the reader is left to guess at the identity of the features in Fig.2d.

⇒ We thank the reviewer for the comment. We added markers to guide the reader to identify from which z-slice the intensity slices were taken from.

- The start shaped high dose (suggest changing intensity to dose again here) in Fig. 2d is curious. I suppose this is an artifact of the square chamber? Were similar bright regions occurring in Fig. 1? Could these be eliminated or reduced using a different optimization approach (perhaps a different loss function) or is this a fundamental result of dose application in a square cuvette?

> ⇒ It is most likely a combination of square shaped vial and occlusion. Since the intensity variations are within the limits of the loss function, it is not a critical issue. More homogeneous intensities in object space can be achieved by tuning the thresholds T_L and T_U inside the loss function. However, this comes at the cost of less contrast between the thresholds and also energy efficiency.

- Scale bar is required for all insets in this paper (eg. Fig. 2f, 1i,g,h)

> ⇒ We thank the reviewer for pointing this out. We added scale bars in all insets.

- Here the inner diameter of the channels is designed to be 0.7mm. What is the fabricated diameter? The authors should check this experimentally.

> ⇒ We added: The designed channel diameters are 0.95 mm, 0.7 mm and 0.95 mm respectively. Experimentally, we measure (1.15 ± 0.10) mm, (0.5 ± 0.1) mm and (0.6 ± 0.1) mm. The deviations can be explained by slight over- or underpolymerization, swelling of the material, and diffusion of the dye.

- Fig. 3: again, I don't think the histogram adds any insight. The histogram improvement looks marginal, but from the intensity (dose) slices one can immediately see the value.

> ⇒ We agree, and moved the histograms for completeness into the supplementary. We keep one histogram in Figure 1 as an example as it provides an interesting insight for first-time readers.

- For the reflective rod experiment, it would be interesting to have a supplementary figure showing a slice of the simulated intensity resulting from illuminating the rod with a uniform intensity from one direction. This would give the reader a graphical understanding of how the rod is modelled.

> ⇒ We included a figure to describe the Beckmann distribution (see below).

- How did the Authors arrive at the parameter alpha=0.04 used for the Beckmann distribution for the rod? This seems important – an incorrect alpha value might even be worse than the non-reflective model.

> ⇒ We estimated it from visual appearance by varying the parameter α in simulation.

- I think it would be useful to elaborate a bit more on the optical model of the rod, since printing over a reflective object is a major point of novelty of this paper. Does the Beckmann distribution's alpha parameter determine the overall amount of light reflection? Does it determine the angular spread of reflected light? I see there is a reference, but I think it would be very helpful for the reader to distill and convey the essence of this model in the main body of the manuscript.

> ⇒ The Beckmann distribution's alpha parameter represents the angular spread of the light scattered from the metal rod. We added a figure in the supplementary the make the qualitative impact of α visible (see Figure 9).

- There is no discussion of the adhesion of the gear on the rod. For example, if someone were to push on the gear lightly, does it stay on the rod? This is an import aconsideration for overprinting. Perhaps the authors could show a video that qualitatively demonstrates the adhesion strength?

⇒ Thank you for raising this point. After drying and post-curing, the gear sticks firmly onto the metal rod. Following the reviewer suggestion, we added a video (see S4) where we push the gear with a flexible ruler (to visualize the varying force). Adhesion is still significant after several months and no displacement of the gear was observed.

- *"By selecting the optimal threshold, we achieved a high fidelity print with IoU..." This should be changed to something like "This optimized projection set reaches a simulated IoU of...". The IoU here is not measured from the actual print, but instead from the simulated dose.*

⇒ We agree with the comment, and implemented this change.

- *Fig 4: The geometry of this experiment is really not clear. How is the LED placed in the vial and what does it look like? Its size? It would help to have a photograph of just the LED, potentially in its mount, to understand what is going on here. Or perhaps a CAD drawing.*

⇒ We added an explanatory figure in the main text to make the geometry clearer (Figure 4f). We hope this makes it clear. Further, we repeated this experiment.

- *Fig 4a: I really don't think this is necessary in the main body – I would suggest to move to supplementary.*

⇒ We believe that the schematic of Figure 4a is important for the reader to better understand the functioning of the LEDTVAM setup. This figure mirrors Figure 1a (schematic of LaserTVAM) making it easier to appreciate the critical differences. It therefore provides a natural entry point into the second section of the manuscript, which concentrates solely on LED-based, striation-free prints.

- *Fig. 4c: indicate where this slice is taken in the 3D rendering in Fig. 4e.*

⇒ We included the absolute position and some visual markers to resolve this.

- *For this experiment, what is the design focal length or surface radii of the fabricated lens? Is the fabricated lens close to the design? How far away is the screen in Fig. 4g? Is the image supposed to be created at a particular distance from the lens? There is a lot of information missing in this section.*

⇒ The initial design was a focal length of 4 mm, as mentioned in the manuscript. However, we did change the model for an improved, more stable version (see new Figure 4). The new lens has a designed focal length of around 4.97 mm. We added this to the manuscript: The radius of curvature of the lens surfaces is 4 mm, the experimental measured radius of curvature is (4.08 ± 0.05) mm.

- *From the pattern is Fig. 4d, it's not clear that the occlusion of the LED is making any difference to the projections. I would expect to see a darker region indicating the LED at the top, but I don't see any. Could the authors outline the region where the LED is located in Fig. 4g?*

⇒ To improve clarity, we provide a new figure arrangement that makes the LED location clear. Since the refractive index is very close to the one of the resin, the visual impact is very little. However, there is a subtle impact on the brightness.

- *Colorbars in this figure are all missing labels and units.*

⇒ If reviewer is referring to Figure 4, we believe that there are color bars and labels. There are no units as we use dimensionless intensities and dose in simulation.

- The authors mention that this print required overpolymerization. How are the authors determining when to terminate the print? Was it trial and error? It would seem that this is a design or optimization issue. Eitther the design should be modified so the pillars are thicker or the optimizer is not actually converging on a uniform dose everywhere.

⇒ We thank you for the valuable suggestion. We indeed improved the model design to feature thicker pillars. This resulted in better stability and firm adhesion to the LED without need for overpolymerization.

- Fig. 5: Again I don't think Fig. 5a is required here, and in this figure, the DMD is not visible so the meaning of the red and blue rays is not clear without looking at Fig. 4 and inferring.

⇒ Yes, we agree with the reviewer as this might look repetitive, particularly in the main text. We moved this part entirely to the supplementary information.

- I don't really find this experiment very compelling. The image in Fig. 5g is very hard to interpret. I would suggest removing this experiment from the paper as the previous experiments in the manuscript are better examples of this technique.

⇒ We agree with the reviewer and removed the experiment from the main text. However, as it still does demonstrate an interesting and challenging overprinting case, we kept these results in the supplementary information.

- "Notably, LEDTVAM setups are not possible to simulate with other existing software solutions." I disagree with this statement. All of the previous TVAM papers that use LEDs do simulate dose to some degree of accuracy. In particular Daniel Webber et al., "Versatile volumetric additive manufacturing with 3D ray tracing," Opt. Express 2023 does something very similar to the technique in this paper, however, it is not used for overprinting. I suggest to modify this statement to be more clear that the authors are referring to overprinting and not TVAM in general.

⇒ Thank you for rightly pointing to this prior work which we have already referenced. We changed our sentence to: Notably, LEDTVAM setups are not possible to simulate with other existing **open-source** software solutions to this extent. To our best knowledge, the package 3DRT prestend by Webber et al. is not released publicly. Yes, in principle conventional TVAM software can simulate LED setups to some extent but they results in non-ideal prints since they do not model non-telecentricity and defocus blur. Depending on the specific parameters the impact can be very significant.

- "Furthermore, our overprinting approach enables the direct fabrication of microfluidic biomimetic channels without the need for additional post-processing or assembly steps, thereby minimizing the risk of contamination and mechanical damage. To our knowledge, this is the first time this has been demonstrated with TVAM based methods.". I this this is a great result in the paper. However, it is not the first such demonstration: https://readily3d.com/wp-content/uploads/2025-05-20-PR-On-chip-printing.pdf.

⇒ Thank you for your reference. Readily3D's demonstration is not true overprinting as they only print very simple "obstructive structures, such as pillars". Further, they do not disclose details on the manufacturing and optimization side. To the best of our knowledge their approach relies on immersing the chip in index matching bath. Also, it remains unclear how they are able to print arbitrary 3D structures (which are not shown in the link, limiting the examples to very simple pillars) inside a flat chip with limited angular availability. We believe that our true 3D examples are significantly different and allow the manufacturing of more complex structures inside flat chips. However, we added this reference for completeness.

- I think it is a bit of a stretch to say that the channels printed in this paper are "vascular-like". They need to be significantly more complex to approach vascular networks.

⇒ We agree with you and changed it to 3D branching networks

- "By incorporating the lens at an appropriate distance from the LED, the system effectively reimages the printed pattern onto the screen, illustrating the potential to integrate arbitrary projection functionalities directly onto compact light sources." There is no indication in the manuscript that there is a particular distance for the screen, not that the lens is designed in such a way to re-image the cross at a particular distance.

⇒ The focal length is roughly 5 mm whereas the object is 6 mm away. The theoretical imaging distance is around 30 mm. To obtain a large projection image of the cross, we did go out of focus at a larger screen distance. As shown in Figure 4, the cross is still clearly visible.

- "Since LED-based setups are not yet common in the literature, we aim to provide a more detailed de scription. The general configuration can be observed in Figure 6a." This is a curious statement since the first peer reviewed published system (Kelly et al. Science 2019) is an LED system, and there have been many since by the CU Boulder and NRC teams to name a few.

⇒ We agree with your remark and removed the ambiguous sentence. Our emphasis was on the ray-optical modeling of the LED aspect. In early TVAM publications, even LED based setups were assumed to be perfectly collimated parallel rays. In our system we explicitly model this defocus blur and hence the pattern optimization is able to compensate for this blur to some extent. This is also along the lines of Webber et al. who modeled blurred light sources in a similar fashion.

- Section 4.7. What is the rationale for the changes in the projected power? One would expect to keep the power the same for each system (laser and LED), but her it seems to be changed randomly. Also, why is the rotation rate changed among the various prints? 47 deg/s is particularly strange.

⇒ Most TVAM simulations (except the ones taking diffusion into account) model the light dose distribution as time-independent phenomena. Hence, changing the rotation speed or projected power is not a significant parameter unless the deposit energy is the same. Changing the power or rotation speed is sometimes limited by maximum output power or speed of each setup. Therefore, in practice we tune rotation speed and/or power to achieve the perfect print. We note that most publications do not disclose details on those printing parameters.
Also, it is important to note that each set of projections has a different pattern efficiency and energy threshold and that our LEDTVAM and LaserTVAM have different wavelengths.

5 Reviewer #2 (Remarks on code availability)

It is more appropriate to review the software at a later date when paper has been significantly revised.

6 Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

7 Reviewer #4 (Remarks to the Author)

This impressive work significantly advances the state of the art in overprinting, whereby photopolymer objects are printed around pre-existing solid structures via specially designed, tomographically reconstructed light patterns. Two key research challenges in this area have been to design projection patterns for specific embedded objects whose positions may exhibit some variability or deviation from intended positions (so-called "context-aware" printing), and also to compensate for reflection or scattering (rather than just absorption) by embedded objects. This manuscript makes significant progress on both challenges.
The result showing the importance of including reflection/scattering when overprinting onto a shiny cylinder are impressive: compared to assuming the shaft to be absorptive, the printing quality is significantly improved. This is an important result for many potential manufacturing applications.
The description of the engineering of the LED-based (as opposed to laser diode-based) system is also a valuable contribution.
I just have one question/comment:
Section 2.2. The work on context-aware printing around silica spheres is impressive and valuable. I am not convinced though that the term "on-the-fly" accurately reflects what was done. The authors used imaging to determine the positions of embedded spheres, then calculated printing patterns. While done impressively quickly (30 s) this was not, to my mind, done "on the fly" in the sense of computation being done at the same time as printing. Therefore the computational speed is a significant advantage but not an integral attribute of the process methodology (i.e. slow computation would be possible; one would just have to wait longer between imaging and printing). Could the authors please clarify this point?

> ⇒ We agree with your remark. On-the-fly is indeed ambiguous here. In this case we were trying to state that we mount the vial, then optimize the patterns and finally print. Usually, pattern optimization is done before the actually printing process (going to the lab and starting to mount vial) and patterns are not changed for each vial. In this case, each vial (with its distinct spheres position), is printed by new patterns. To avoid confusion we removed ~~on-the-fly~~ from this sentence.

8 Reviewer #5 (Remarks to the Author)

Summary: The study demonstrates the successful overprinting of different shapes for different applications using Tomographic Volumetric Additive Manufacturing (TVAM) method. For this purpose, the newly developed light pattern generation algorithm, Dr.TVAM, with the capability of accounting for the occlusions and changes of the refraction indices in the light propagation, has been used. The authors have reported successful overprints for different applications including bio-applications and optics, while using both laser and LED light sources. While the overprinting examples are more advanced compared to the ones mentioned in the literature and the examples show the capabilities of the light pattern generator algorithm that is suggested by the authors, the concept of overprinting *as well as printing in vials with non-circular cross-sections have already been documented in the literature, and accordingly the study does not represent a significant novelty. Nonetheless, the authors are recommended to address the following points in the manuscript.*

⇒ We respectfully emphasize that our study introduces experimentally verified advances in tomographic volumetric additive manufacturing (TVAM). Although overprinting has been reported previously, existing demonstrations either neglected the occluding element or assumed complete absorption of previously printed regions. Both simplifications impose fundamental limitations on print fidelity and material compatibility. By explicitly accounting for refracted or scattered light on existing elements, our framework enables high-quality overprinting across a broad range of resins and scenarios. The comprehensive experimental results presented in the revised manuscript, including complex refractive and reflective targets, would not be attainable without these contributions.

1- In all the histograms that are presented in this paper, there is a huge overlap between the object and void voxels. It has been shown and discussed in the literature that a gap between the two can improve the quality of the prints and help to prevent the undesired under- and over-curing.

⇒ It should be noted that the histogram is in logarithmic scale, so the absolute overlap is very small. We agree with the reviewer that a larger gap is desirable. The overlap here, comes (mostly) from small artefacts such as parts of the objects being inside the occlusions or slightly outside of regions reachable by light. Also, since our rendering is Monte Carlo based there is always some noise. In a linear scale, this noise is not visible and does not reduce printing quality as indicated by high IoUs.

It is necessary that the authors explain and discuss the reason for this overlap and discuss how it affects the print quality. Additionally, why is the normalized dose of the histograms higher than 1.0? How are the dose values normalized?

⇒ We thank the reviewer for the observation. *Normalized dose* was the wrong term. In simulation it is a unit-less dose. We force the dose so that void regions stay below T_L, and objects regions stay above T_U but also below 1. The final loss value is numerically not 0, so some of the dose can be above 1.We removed the term *normalized dose* and replaced it by *simulated dose.*

2- In the printing patterns shown in Fig. 2e, the in-part regions or object voxels, are darker than the surrounding medium around them. This seems counterintuitive, as the in-part regions should receive a higher dose and accordingly look brighter in the light patterns. Some explanation in this regard can improve the understanding of this figure.

⇒ We believe the brighter regions you refer to are actually the light absorbing occlusions. Hence, our patterns send more light onto those regions as there is light loss which needs to be compensated by higher intensity.

3- It is mentioned that the overprinting process in the context-aware perfusion system (section 2.2) takes around 3 minutes to complete (from taking the images to completing the print). How is the vertical movement of the silica beads, namely the movement due to gravity and other forces (buoyancy and local drag forces due to the convective effects induced by exothermic reactions), controlled or taken into account?

⇒ In this experiment we used Gel-MA as resin. After being cooled to 4 °C, GelMA transitions to a gel state and remains solid at room temperature, and hence no movement of the beads is observed. We added a sentence in the manuscript to highlight this fact.

4- In Fig. 4, there is a considerable difference between the 3D rendering and the printed part. Authors have mentioned that LED-printing leads to lower accuracy compared to laser printing. However, the convex surface of the lens (Fig. 4e) is observed to be printed as a concave surface (Fig. 4f), which is quite a considerable difference.

⇒ This was just an optical illusion. The lens surface is indeed convex as it should be. However, we reworked this experiment and replaced the old results with new results which should make it more clear.

It is important that the authors clarify on the reasons behind this issue and argue when the low-accuracy prints of LED-based printing can be useful. Regarding the striations, Rackson et al suggested a method to mitigate this issue for laser printing. Why didn't the authors use that methodology to tackle the striation challenge for higher surface qualities.

⇒ The proposed method of Rackson et al. requires careful tuning between timings of laser illumination and LED illumination. If the timing is chosen wrong, striations might still occur. Further, since the LED light is also absorbed, taking attenuation into account is important to achieve goods prints. We believe this methodology is experimentally relatively complex and from the theoretical standpoint hard to calibrate (the diffuse light distribution of the entire LED and refraction into the vial from the bottom would need to be modeled for a full understanding of the absorbed dose) .
We did indeed use a non-collimated LED light source as proposed by Webber et al. in 2024. As it can be seen, the parts are free of striations which was also the motivation to use a LED illumination instead of a laser illumination in that setup. As seen in Figure 4b, LED printers can still produce sharp and high accuracy intensity distributions. It does require less experimental tuning to obtain a good print.

Additionally, the LED-based print represented in Fig. 5 seems to have a higher quality, though the authors have not put any image of the rendered geometry. It would be nice if the authors made a comparison between the STL files that have been used for the printing and the final prints to show the fidelity of the prints.

⇒ We moved this section to the supplementary. Figure 6c) indeed shows the simulated, ideal dose.

5- In the Discussion section, the authors claimed that the overprinting of microfluidic channels did not require any post-processing stage. Why did not this or other prints in this study require a post-curing stage, where the partially cured parts are exposed to prolonged UV exposure?

⇒ In principle, none of the prints require post-curing as the solid constructs are formed when exceeding the gelation threshold. Post-curing simply increases the stability/stiffness of the print by completing polymerization. We indeed performed post-curing for all prints, as discussed in Materials and Methods. With regard to the microfluidic channels, the post-processing discussion aimed at highlighting that the printed construct does not need to be taken out of the vial for washing, curing and other steps. We understand that this wording could be misleading, so to avoid confusion, we removed the sentence from the main text.

6- Minor comment: In the last line of the first paragraph of the Introduction section, the word "exceeds" is repeated.

⇒ We fixed this typo.

Response to reviewer's comments

In the following, we would like to respond to the reviewers' comments. We made significant changes to the manuscript to include the suggestions.
In general, all changes in the manuscript are indicated by the following color codes:

- Added text looks like this
- ~~Removed text looks like this~~

All new configuration and mesh files are currently available over: https://go.epfl.ch/overprinting_revisions

1 Replies to the reviewers

In the following we reply to all reviewer comments in red color.

2 Reviewer #1 (Remarks to the Author):

This authors have done a good job addressing reviewer comments and the paper is now suitable for publication. Typo note: In Section E of the SI the figure number used is 8 and it should be 10. I applaud keeping the dose histograms in the SI rather than deleting them as suggested by another reviewer. I found them to be particularly useful.

⇒ Thank you for pointing out the mistake, we corrected it.

2.1 Reviewer #1 (Remarks on code availability):

The code is clear and complete.

3 Reviewer #2 (Remarks to the Author):

I commend the authors for making many improvements in the paper.
However, I cannot yet recommend this paper for publication for one main reason: the authors have still not experimentally demonstrated improved results with reflective objects that could not have likely happened by other means (namely over or under exposure).
For this, the authors present Section 2.3 "Gear on Metal Rod". Here a gear is overprinted onto a reflective metal rod. However, as I said in the initial review, there is little in the result of Fig. 3c/g to show that the reflection-corrected light patterns make any difference to the print. The authors show that with the uncorrected patterns, the hole is 0.71mm in diameter and with the corrected patterns, the hole is 0.96mm. There are several issues with this:
1. These measurements are made from an oblique angle, and for the 0.71mm hole, it appears that the authors are measuring from the left side on top of the hole to the right side on the bottom of the hole. By my measurement of the image, the true diameter of the hole is a bit larger, about 0.84mm. This is less than the design value (0.90mm)

by the same amount as the scattering corrected print is too large (+/- 0.06mm), which is 0.96mm. The difference in print dimensions is actually very small, and equally erroneous on both prints. Furthermore, there is no error provided on the measurement of the hole diameter. There is more than one hole in the gear. Why not measure all of them and take the mean +/- standard deviation? One should also measure whether there is a difference in the hole diameter along different orientations. Is the hole truly circular? All of this gets at the following point: the hole is slightly off from the design value... is this difference in hole dimension between scattering and no scattering correction statistically significant or not and does it necessarily stem from the scattering or could it have happened due to global exposure differences?

⇒ Thank you for pointing out the perspective errors. We added a new set of experiments with images captured orthogonally. Please see the additional comments below, as well as Figure 3 and Figure 9 in the manuscript.

2. How do we know the difference in size isn't simply because of slight over or under exposure? At these length scales (+/- 60µm), VAM is very sensitive to exposure time. The authors should show that this difference is repeatable, and not just the result of two prints with manually controlled exposure times. I actually do believe that the scattering correction is making a difference here, but for a paper in Nature Comms, I would expect to have a more compelling dataset for the most definitive and novel part of the paper. One possible route is the following: measure the size of the gear teeth (positive feature) and holes (negative) for different exposure times. If the scattering correction is working as intended, the teeth and holes should either underexposed (teeth too small, hole too big) or overexposed (teeth too big, hole too small). If scattering correction is not compensating properly, then there will be an exposure time that leads to the teeth being too small (under exposed) and holes being too small (over exposed). For the current data in Fig. 3, which situation do we have? One could consider also printing both corrected and uncorrected gears onto the same rod in the same print for comparison. I encourage the authors to come up with an improved test print geometry to unequivocally show that the scattering correction enables printing of an object that is not otherwise possible in the presence of reflection/scattering.

3. The reason why I belabour #2 above is because the stated method for estimating the only reflection/scattering parameter (alpha) is "we assumed a value of alpha = 0.04 which was visually matched to comparison renderings". This approach is fraught with issues: it is qualitative, it depends on the monitor and rendering software. Does the lighting in real life match that in the rendering? Would different observers estimate different alpha values? And so on... This is the sole extra parameter responsible for calculation of the scattering effect on the patterns, yet it is not even known/estimated quantitatively. And so therefore, even if it is helping to improve the overprint quality, it is some sense accidental that the correction is not over or under correcting.

For this reason I strongly encourage the authors to measure some aspect of the reflection and match it to a Beckmann distribution. For example, perhaps the relative intensity at a few different reflected angles could be measured experimentally and then a Beckmann distribution could be fitted to the result. It need not be a complex measurement, and would add significant weight to the claim that this model and the associated corrections are accurately correcting the projections.

⇒ Thank you for your comment. We agree that our initial calibration of the α parameter was vague and not sufficiently quantitative. Indeed, we followed your suggestion and tested the reflection of single pixels in a fluorescent dye. From the spread of the reflected light cone, we were able to obtain a fairly accurate estimate of the α parameter. Please note that, due to shipping constraints, we had to purchase a different metal rod, which appeared to be slightly more polished. The resulting calibrated scattering parameter, $\alpha = 0.03$ (the previous rod had $\alpha = 0.04$), was added to Figure 3 and also to Supplementary Note E. We hope that this provides a more rigorous calibration.

⇒ We also agree with your comment that the previous results could have been caused by variations in exposure. To make the final results more convincing, we conducted a fine exposure series using both patterns, added as Supplement D. None of the exposures with the scattering-ignoring pattern achieved hole quality comparable to that obtained with the scattering-corrected pattern. Both the simulations and the experiments confirm artefacts similar to those observed previously. This should sufficiently demonstrate that underexposure or overexposure does not explain the resulting artefacts.

I am impressed with the new supplementary section B Dice on Mirror. In the reflection-aware case, the dice is no longer connected to the mirror, Is that correct? If so, perhaps the authors could image it more clearly on a different background with more contrast? I am a little surprised that the simulation/print comes out mostly OK when the mirrors are assumed to be absorbing and non-reflecting.

⇒ Thank you for your response. We were also surprised that the reflection-ignoring patterns performed well in both simulation and experiment. However, we believe that most of the information is still transmitted correctly, and only part of the back-reflection is inaccurately represented. Because of the relatively high absorbance, the patterns nevertheless appeared to work well. Indeed, the main difference was that the reflection-correcting patterns resulted in a dice attached to only one mirror. In contrast, for the reflection-ignoring patterns, the gap was not well preserved, and the dice adhered to both surfaces.

Final comment on Fig. 4. Could the authors improve the imaging of the cross (Fig. 4g)? Perhaps the projected image could be demagnified and projected onto a camera sensor. I suggest to refrain from vague scale bars ("around 10cm") and instead use an imaging arrangement where scalebars can be properly known.

⇒ The idea of the projector system is to project the cross onto a screen or wall. Re-imaging the entire cross would only add unnecessary complexity. Consequently, the size of the cross depends on the distance to the projector, as this is approximately an infinity-projection imaging configuration in which a range of projector distances still produces recognizable cross shapes.

4 Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

⇒ Thank you for your effort and deep comments.

5 Reviewer #4 (Remarks to the Author):

My earlier comment has been satisfactorily addressed.

⇒ Thank you for your engagement in reviewing our work!