Deep Learning for Multi-Path Error Removal in ToF Sensors *Additional Material*

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1 Analysis of the MPI Removal Capabilities on Corner Scenes

In this document we present a detailed analysis of the MPI removal capabilities for the proposed and competing approaches on corner scenes. We considered the same methods used in the *Results* section of the paper, i.e.:

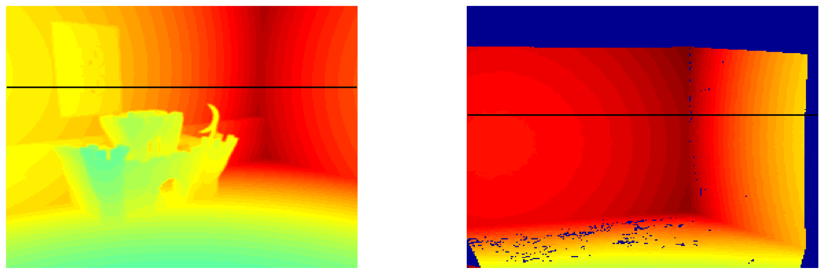
- The method proposed by Freedman et Al. [1] (SRA) that uses multi-frequency data from a ToF camera and solves MPI with a L_1 *optimization* under the assumption of sparsity in the light backscattering response.
- The method proposed by Marco et Al. [2] (DeepToF), that is based on a deep learning approach that has in input a ToF depth map at 20 MHz.
- Our approach with and without the final refinement based on the proposed adaptive bilateral filter.

For this analysis we considered corner scenes because they are the most common situation where MPI arises. We performed the analysis on both synthetic and real data: Fig. 1 shows the two corner scenes (one from the synthetic dataset, the *castle* scene, and the other from the real dataset) that have been considered.

2 Corner on Synthetic Data

Fig. 2 shows the depth maps estimated with the considered methods and their error images, while Fig. 3 shows a detail of the estimated depth maps on an horizontal profile crossing the corner region.

Starting from the method of Freedman et Al. [1], it seems to have a limited capability of removing the multi-path interference and its output generally stays quite close to the original data. This is mostly due to the assumption that the light backscattering response is sparse: this is not satisfied on the considered scene that has strong diffuse reflections. The method of Marco et Al. [2] is able to generally reduce MPI corruption, but the final result is not completely precise: the depth is overestimated in some regions and underestimated in others. Our method proved to be the best solution: it never creates artifacts due to an overestimation of the MPI and it is able to remove most of the MPI corruption.



a) b)

Fig. 1. Analyzed corner scenes: a) synthetic *castle* scene; b) real world corner scene (the dark blue points have no ground truth info). The horizontal line highlights the profile used for the plots in Figs. 3 and 5.

However a bit of multi-path error is still present after the application of the method. Moreover, it is possible to notice how the adaptive bilateral filter used in our approach greatly reduces the level of the zero-mean noise if compared with the solution given by the CNN alone.

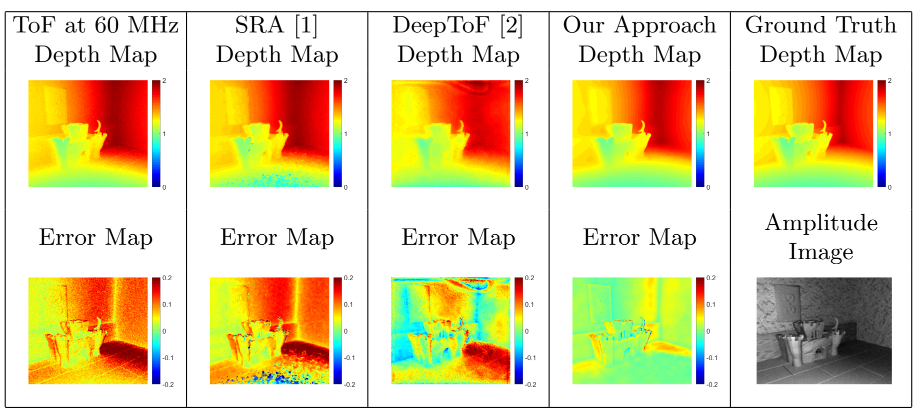


Fig. 2. Depth maps and error maps for the compared methods on the *castle* synthetic scene: input data, [1], [2] and the proposed method. The last column shows ground truth information and the amplitude image from the sensor. All the values are measured in meters.

3 Corner on Real World data

On real data (Figs. 4 and 5) the behavior is similar, the Freedman method slightly reduces MPI, but not in a satisfactory way. The method of [2] has better

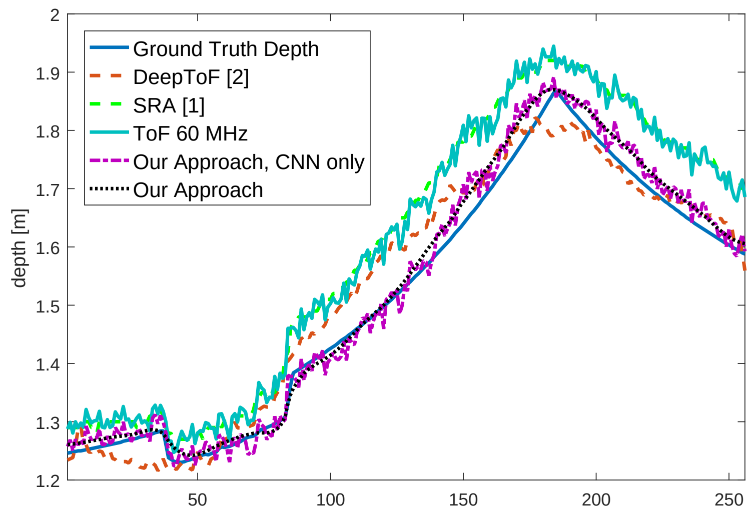


Fig. 3. Estimation of the depth in proximity of a corner on the synthetic data: the figure shows the depth estimation for the compared methods in the points corresponding to the highlighted horizontal line in Fig. 1a and compares the data with ground truth depth.

performances in this case, it obtains very good results on the right part of the scene that is strongly affected by MPI, but notice how on the left part, where the corruption is smaller, an underestimation of the depth (due probably to an overestimation of MPI) is noticeable. Also in this case our approach has the best and more stable results and thanks to the adaptive bilateral filter it is also able to reduce the zero-mean noise contained in the source data. Please notice that our approach (but also the others) is not able to completely correct MPI present on the floor of the scene. A discussion about this issue can be found in the *Results* section of the paper.

References

1. Freedman, D., Smolin, Y., Krupka, E., Leichter, I., Schmidt, M.: Sra: Fast removal of general multipath for tof sensors. In: Proceedings of European Conference on Computer Vision (ECCV), Springer (2014) 234–249
2. Marco, J., Hernandez, Q., Muñoz, A., Dong, Y., Jarabo, A., Kim, M.H., Tong, X., Gutierrez, D.: Deeptof: off-the-shelf real-time correction of multipath interference in time-of-flight imaging. ACM Transactions on Graphics (TOG) **36**(6) (2017) 219

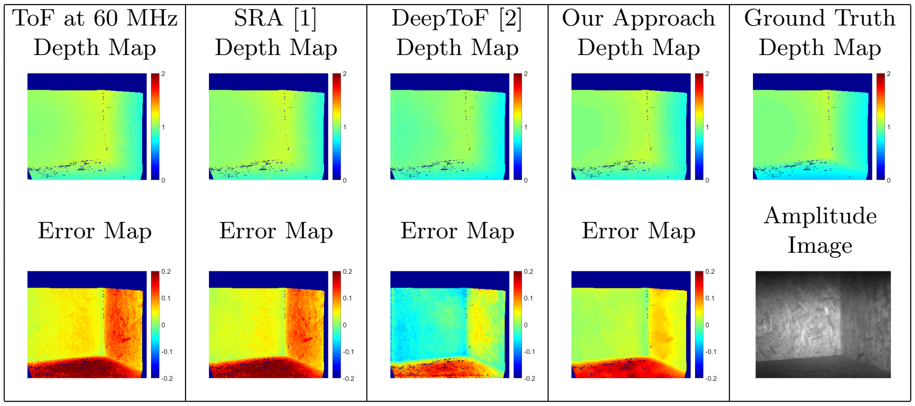


Fig. 4. Depth maps and error maps for the compared methods on the real world corner: input data, [1], [2] and the proposed method. The last column shows ground truth information and the amplitude image from the sensor. All the values are measured in meters.

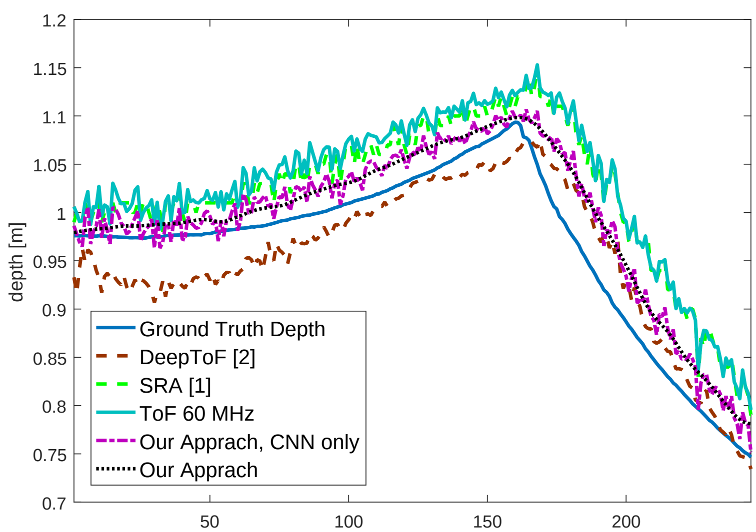


Fig. 5. Estimation of the depth in proximity of a corner on real world data: the figure shows the depth estimation for the compared methods in the points corresponding to the highlighted horizontal line in Fig. 1b and compares the data with ground truth depth.