

Output: ① the scene geometry
② the mapping between pixel-3d points
③ the relation between viewpoints

DUST3R: Geometric 3D Vision Made Easy

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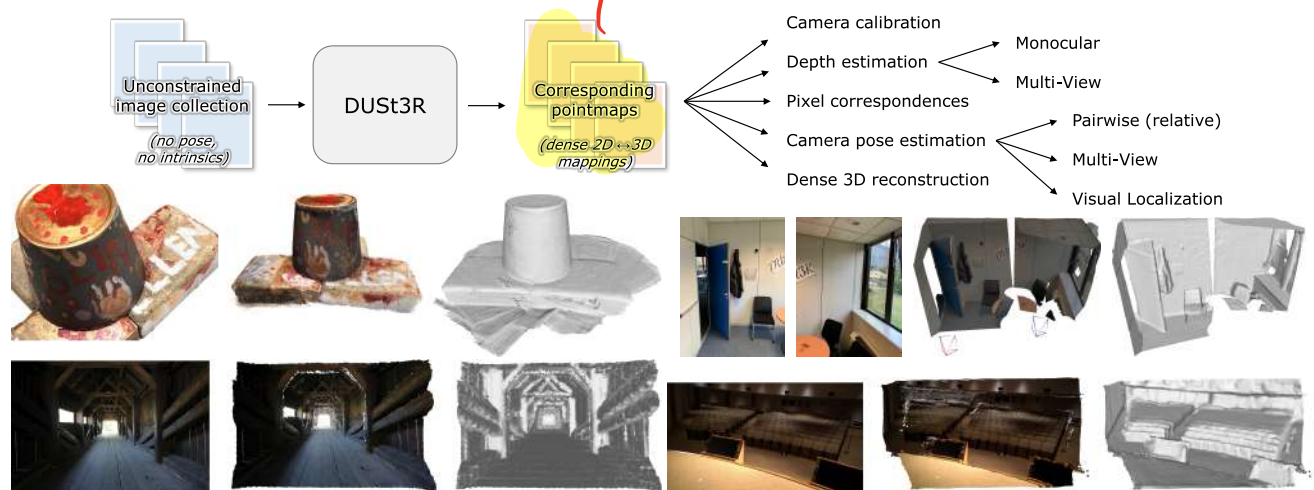


Figure 1. **Top:** DUST3R takes as input an unconstrained collection of images and outputs pointmaps, from which various geometric quantities can be straightforwardly derived. **Bottom:** Fully-consistent 3D reconstructions without input camera poses nor intrinsics. From left to right: input image, colored point-cloud, rendered with shading. DUST3R can also reconstruct scenes without any visual overlap (top-right).

MVS: Input: A set of posed and calibrated images of a scene

Abstract

Multi-view stereo reconstruction (MVS) in the wild requires to first estimate the camera intrinsic and extrinsic parameters. These are usually tedious and cumbersome to obtain, yet they are mandatory to triangulate corresponding pixels in 3D space, which is at the core of all best performing MVS algorithms. In this work, we take an opposite stance and introduce **DUST3R**, a radically novel paradigm for **Dense and Unconstrained Stereo 3D Reconstruction** of arbitrary image collections, operating without prior information about camera calibration nor viewpoint poses. We cast the pairwise reconstruction problem as a regression of pointmaps, relaxing the hard constraints of usual projective camera models. We show that this formulation smoothly unifies the monocular and binocular reconstruction cases. In the case where more than two images are provided, we further propose a simple yet effective global alignment strategy that expresses all pairwise pointmaps in a common reference frame. We base our network architecture on standard Transformer encoders and decoders, allowing us to leverage powerful pretrained models. Our formulation directly provides a 3D model of the scene as well as depth information, but interestingly, we can seamlessly recover from it, pixel matches, focal lengths, relative and absolute cameras. Extensive

experiments on all these tasks showcase how DUST3R effectively unifies various 3D vision tasks, setting new performance records on monocular & multi-view depth estimation as well as relative pose estimation. In summary, DUST3R makes many geometric 3D vision tasks easy. Code and models at <https://github.com/naver/dust3r>.

1. Introduction

Unconstrained dense 3D reconstruction from multiple RGB images is one long-researched end-goal of computer vision [21, 58, 72]. In a nutshell, it is the task of estimating the 3D geometry and camera parameters of a particular scene, given a set of photographs of this scene. Not only does it have numerous applications like mapping [12, 59], navigation [13], archaeology [70, 99], cultural heritage preservation [37], robotics [63], but perhaps more importantly, it holds a fundamentally special place among all the tasks from the 3D vision research field. Indeed, it subsumes nearly all geometric 3D vision tasks, and modern approaches for 3D reconstruction thus consists in a sequential succession of many components, such as keypoint detection [23, 26, 53, 77] and matching [9, 51, 81, 92], robust estimation [3, 9, 137], Structure-from-Motion (SfM) and Bundle Adjustment (BA) [18, 50, 83], dense Multi-

→ problem = lack of communication (collaboration)

View Stereo (MVS) [84, 103, 119, 134], etc. This rather complex chain is of course a viable solution in some settings [30, 57, 61, 106, 110, 112, 123], yet we argue it is quite unsatisfactory: each task is not solved perfectly and adds noise to the next step, increasing the complexity and the engineering effort required for the pipeline to work as a whole. The absence of communication between each component is also quite telling: it would seem more reasonable if they helped each other, *i.e.* dense reconstruction should naturally benefit from the sparse scene that was built to recover camera poses, and vice-versa. On top of that, key steps in this pipeline are brittle and prone to break in many cases [50]. For instance, the crucial stage of SfM that serves to estimate all camera parameters is typically known to fail in many common situations, *e.g.* when the number of scene views is low [85], for objects with non-Lambertian surfaces [14], in case of insufficient or overly large camera motion [12], etc.

In this paper, we present **DUST3R**, a radically novel approach for Dense Unconstrained Stereo 3D Reconstruction from un-calibrated and un-posed cameras. The main component is a network that can regress a dense and accurate scene representation solely from a *pair* of images without prior information regarding the scene nor the cameras (not even the intrinsic parameters). The resulting scene representation is based on *3D pointmaps* with rich properties: they simultaneously encapsulate (a) the scene geometry, (b) the relation between pixels and scene points and (c) the relation between the two viewpoints. From this output alone, practically all scene parameters (*i.e.* cameras and scene geometry) can be straightforwardly recovered. This is possible because the network jointly processes the input images and the resulting 3D pointmaps, thus learning to associate 2D patterns with 3D shapes and having the opportunities of solving multiple tasks simultaneously, enabling internal ‘collaboration’ between them.

Our model is trained in a fully-supervised manner using a simple regression loss, leveraging large public datasets for which ground-truth annotations are either synthetically generated [56, 82], reconstructed from SfM softwares [47, 122] or captured using dedicated sensors [22, 75, 94, 126]. We drift away from the trend of integrating task-specific modules [125], and instead adopt a fully data-driven strategy based on a generic transformer architecture, not enforcing any geometric constraints at inference, but being able to benefit from powerful pretraining schemes [114]. The network learns strong geometric and shape priors, which is reminiscent of those commonly leveraged in MVS, like shape from texture, shading or contours [87].

To fuse predictions from multiple images pairs, we revisit bundle adjustment (BA) for the case of pointmaps, hereby achieving full-scale MVS. We introduce a global alignment procedure that, contrary to BA, does not involve minimizing reprojection errors. Instead, we optimize the camera

poses and the scene geometry directly in 3D space, which is fast and shows excellent convergence in practice. Our experiments show that the reconstructions are accurate and consistent between views in real-life scenarios with various unknown sensors. We further demonstrate that the same architecture can handle *real-life* monocular and multi-view reconstruction scenarios seamlessly. Examples of reconstructions are shown in Fig. 1 and in the accompanying video.

In summary, our contributions are fourfold. First, we present the first *holistic end-to-end 3D reconstruction pipeline* from un-calibrated and un-posed images, that unifies monocular and binocular 3D reconstruction. Second, we introduce the pointmap representation for MVS applications, that enables the network to predict the 3D shape in a canonical frame, while preserving the implicit relationship between pixels and the scene. This effectively drops many constraints of the usual perspective camera formulation. Third, we introduce an optimization procedure to globally align pointmaps in the context of multi-view 3D reconstruction. Our procedure can extract effortlessly all usual intermediary outputs of the classical SfM and MVS pipelines. In a sense, our approach unifies all 3D vision tasks and considerably simplifies over the traditional reconstruction pipeline, making DUST3R seem simple and easy in comparison. Fourth, we demonstrate promising performance on a range of 3D vision tasks. In particular, our all-in-one model achieves state-of-the-art results on monocular and multi-view depth benchmarks, as well as multi-view camera pose estimation.

2. Related Work

For the sake of space, we summarize here the most related works in 3D vision, and refer the reader to Sec. B of the supplementary for a more comprehensive review.

Structure-from-Motion (SfM) [18, 19, 40, 42, 83] aims at reconstructing sparse 3D maps while jointly determining camera parameters from a set of images. The traditional pipeline starts from pixel correspondences obtained from keypoint matching [4, 5, 39, 53, 80] between multiple images to determine geometric relationships, followed by bundle adjustment to optimize 3D coordinates and camera parameters jointly. Recently, the SfM pipeline has undergone substantial enhancements, particularly with the incorporation of learning-based techniques into its subprocesses. These improvements encompass advanced feature description [23, 26, 77, 101, 127], more accurate image matching [3, 15, 27, 28, 51, 65, 81, 92, 96, 107], featuremetric refinement [50], and neural bundle adjustment [49, 116]. Despite these advancements, the sequential structure of the SfM pipeline persists, making it vulnerable to noise and errors in each individual component.

MultiView Stereo (MVS) is the task of densely reconstructing visible surfaces, which is achieved via triangulation between multiple viewpoints. In the classical formulation of

Unify

Drop representation

★

problem of SfM

MVS, all camera parameters are supposed to be provided as inputs. The fully handcrafted [31, 33, 84, 111, 133], the more recent scene optimization based [30, 57, 60, 61, 106, 110, 112, 123], or learning based [45, 55, 69, 121, 124, 136] approaches all depend on camera parameter estimates obtained via complex calibration procedures, either during the data acquisition [1, 20, 85, 126] or using Structure-from-Motion approaches [42, 83] for in-the-wild reconstructions. Yet, in real-life scenarios, the inaccuracy of pre-estimated camera parameters can be detrimental for these algorithms to work properly [78]. In this work, we propose instead to directly predict the geometry of visible surfaces without any explicit knowledge of the camera parameters.

Direct RGB-to-3D. Recently, some approaches aiming at directly predicting 3D geometry from one or two RGB images have been proposed. Since the problem is by nature ill-posed without introducing additional assumptions, these methods leverage neural networks that learn strong 3D priors from large datasets to solve for ambiguities. These methods can be classified into two groups. The first group leverages class-level object priors [66–68] or diffusion models to generate novel views for object-centric reconstruction [52]. A second group of works, closest to our method, focuses instead on general scenes. When starting from a single image, an extensive usage of monocular depth estimation networks is made [6, 73, 129, 131]. Depthmaps indeed encode a form of 3D information and, combined with camera intrinsics, can straightforwardly yield pixel-aligned 3D point-clouds. SynSin [115], for example, performs new viewpoint synthesis from a single image by rendering feature-augmented depthmaps knowing all camera parameters. If unknown, camera intrinsics can be recovered by exploiting temporal consistency in video frames [35, 90, 117] or regressed by a specialized network [128, 130]. All these methods are, however, intrinsically limited by the quality of depth estimates, which arguably is ill-posed for monocular settings. To solve this issue, multi-view networks for direct 3D reconstruction like DeMon and DeepV2D have been proposed in the past [98, 102, 139]. They are essentially based on the idea of building a differentiable SfM pipeline, replicating the traditional pipeline but training it end-to-end. As before, however, ground-truth camera intrinsics are required as input, and the output is generally a depthmap and a relative camera pose [102, 139]. In contrast, our network outputs pointmaps, i.e. dense 2D fields of 3D points, which handle camera poses implicitly without requiring any camera intrinsic parameters.

Pointmaps. Using a collection of pointmaps as shape representation is quite counter-intuitive for MVS, but its usage is widespread for Visual Localization tasks, either in scene-dependent optimization approaches [7, 8, 10, 24, 46, 108, 109] or scene-agnostic inference methods [76, 95, 120]. Similarly, view-wise modeling is a common theme in monocular

3D reconstruction works [48, 88, 97, 105] and in view synthesis works [115], the idea being to store the canonical 3D shape in multiple canonical views to work in image space. These approaches usually leverage explicit perspective camera geometry, via rendering of the canonical representation.

3. Method

Before delving into the details of our method, we introduce below some essential concepts.

Pointmap. In the following, we denote a dense 2D field of 3D points as a *pointmap* $X \in \mathbb{R}^{W \times H \times 3}$. In association with its corresponding RGB image I of resolution $W \times H$, X forms a one-to-one mapping between image pixels and 3D scene points, i.e. $I_{i,j} \leftrightarrow X_{i,j}$, for all pixel coordinates $(i, j) \in \{1 \dots W\} \times \{1 \dots H\}$. We assume here that each camera ray hits a single 3D point, i.e. ignoring the case of translucent surfaces.

Cameras and scene. Given camera intrinsics $K \in \mathbb{R}^{3 \times 3}$, the pointmap X of the observed scene can be straightforwardly obtained from the ground-truth depthmap $D \in \mathbb{R}^{W \times H}$ as $X_{i,j} = K^{-1} D_{i,j} [i, j, 1]^T$. Here, X is expressed in the camera coordinate frame. In the following, we denote as $X^{n,m}$ the pointmap X^n from camera n expressed in camera m 's coordinate frame:

$$X^{n,m} = P_m P_n^{-1} h(X^n) \quad (1)$$

where $P_m, P_n \in \mathbb{R}^{3 \times 4}$ are the world-to-camera poses for images m and n , and $h : (x, y, z) \rightarrow (x, y, z, 1)$ is the homogeneous mapping.

3.1. Overview

We wish to build a network that solves the 3D reconstruction task for the generalized stereo case through direct regression. To that aim, we train a network f that takes as input two RGB images $I^1, I^2 \in \mathbb{R}^{W \times H \times 3}$ and outputs two corresponding pointmaps $X^{1,1}, X^{2,1} \in \mathbb{R}^{W \times H \times 3}$ with associated confidence maps $C^{1,1}, C^{2,1} \in \mathbb{R}^{W \times H}$. Note that both pointmaps are expressed in the same coordinate frame of I^1 , which radically differs from existing approaches but offers key advantages (see Secs. 1, 2, 3.3 and 3.4). For the sake of clarity and without loss of generalization, we assume here that both images have the same resolution of $W \times H$, but naturally in practice their resolution can differ.

Network architecture. The architecture of our network f is inspired by CroCo [114], making it straightforward to heavily benefit from CroCo pretraining [113]. As shown in Fig. 2, it is composed of two identical branches (one for each image) comprising each an image encoder, a decoder and a regression head. The two input images are first encoded in a Siamese manner by the same weight-sharing ViT encoder [25], yielding two token representations F^1 and F^2 :

$$F^1 = \text{Encoder}(I^1), F^2 = \text{Encoder}(I^2).$$



ray coding

$I_i \leftrightarrow X_{i,j}$

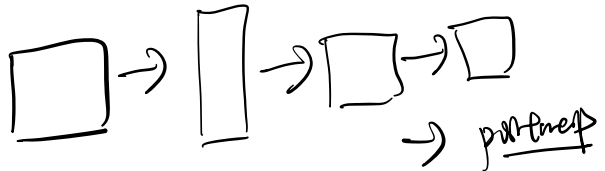
Q4

wait

Q5

$X^{n,m}$

Establish relationship (geometry)



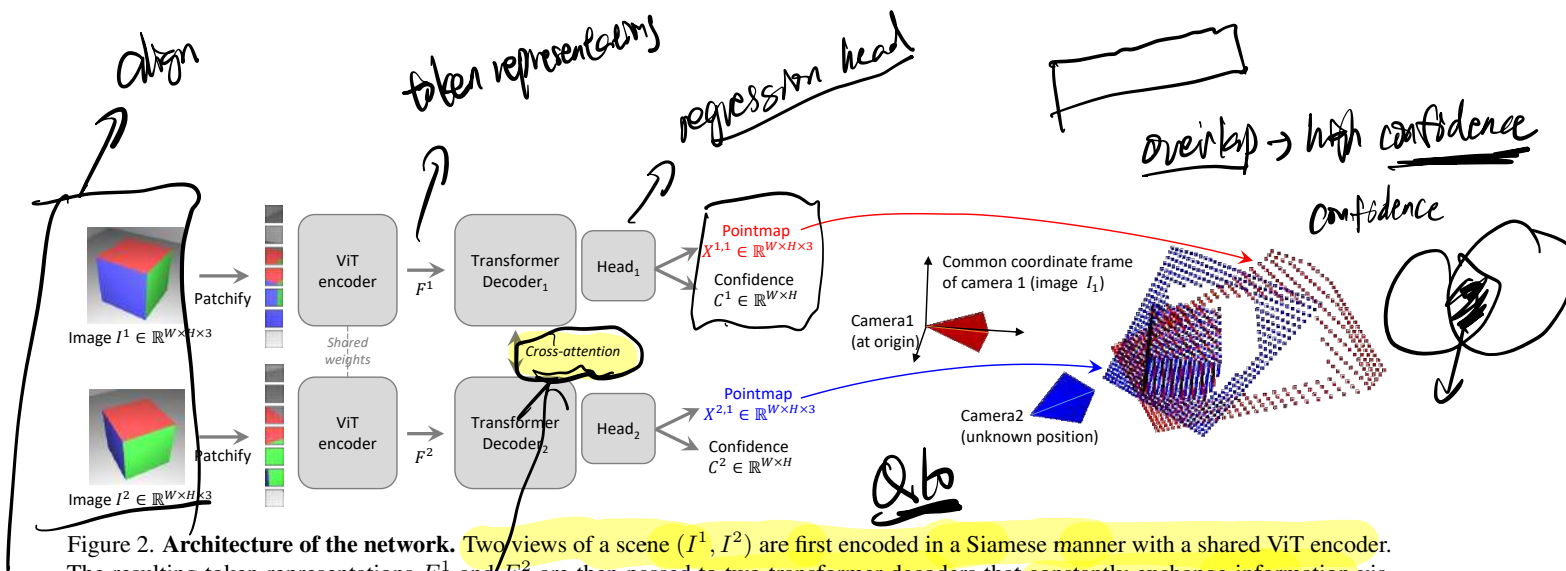


Figure 2. **Architecture of the network.** Two views of a scene (I^1, I^2) are first encoded in a Siamese manner with a shared ViT encoder. The resulting token representations F^1 and F^2 are then passed to two transformer decoders that constantly exchange information via cross-attention. Finally, two regression heads output the two corresponding pointmaps and associated confidence maps. Importantly, the two pointmaps are expressed in the same coordinate frame of the first image I^1 . The network is trained using a simple regression loss (Eq. (4))

The network then reasons over both of them jointly in the decoder. Similarly to CroCo [114], the decoder is a generic transformer network equipped with cross attention. Each decoder block thus sequentially performs self-attention (each token of a view attends to tokens of the same view), then cross-attention (each token of a view attends to all other tokens of the other view), and finally feeds tokens to a MLP. Importantly, information is constantly shared between the two branches during the decoder pass. This is crucial in order to output properly aligned pointmaps. Namely, each decoder block attends to tokens from the other branch:

$$\begin{cases} G_i^1 = \text{DecoderBlock}_i^1(G_{i-1}^1, G_{i-1}^2), \\ G_i^2 = \text{DecoderBlock}_i^2(G_{i-1}^2, G_{i-1}^1), \end{cases}$$

for $i = \overline{1, \dots, B}$ for a decoder with B blocks and initialized with encoder tokens $G_0^1 := F^1$ and $G_0^2 := F^2$. Here, $\text{DecoderBlock}_i^v(G^1, G^2)$ denotes the i -th block in branch $v \in \{1, 2\}$, G^1 and G^2 are the input tokens, with G^2 the tokens from the other branch. Finally, in each branch a separate regression head takes the set of decoder tokens and outputs a pointmap and an associated confidence map:

$$\begin{cases} X^{1,1}, C^{1,1} = \text{Head}^1(G_0^1, \dots, G_B^1), \\ X^{2,1}, C^{2,1} = \text{Head}^2(G_0^2, \dots, G_B^2). \end{cases}$$

Discussion. The output pointmaps $X^{1,1}$ and $X^{2,1}$ are regressed up to an unknown scale factor. It should be noted that our generic architecture never explicitly enforces any geometrical constraints. Hence, pointmaps do not necessarily correspond to any physically plausible camera model (but they closely fit in practice, see Sec. E in the supplementary). Rather, we let the network learn all relevant priors present from the train set, which only contains geometrically consistent pointmaps. Using a generic architecture allows to leverage strong pretraining technique, ultimately surpassing what existing task-specific architectures can achieve. We detail the learning process in the next section.

3.2. Training Objective

3D Regression loss. Our sole training objective is based on regression in the 3D space. Let us denote the ground-

truth pointmaps as $\bar{X}^{1,1}$ and $\bar{X}^{2,1}$, obtained from Eq. (1) along with two corresponding sets of valid pixels $\mathcal{D}^1, \mathcal{D}^2 \subseteq \{1 \dots W\} \times \{1 \dots H\}$ for which the ground-truth is defined. The regression loss for a valid pixel $i \in \mathcal{D}^v$ in view $v \in \{1, 2\}$ is simply defined as the Euclidean distance:

$$\ell_{\text{regr}}(v, i) = \left\| \frac{1}{z} X_i^{v,1} - \frac{1}{\bar{z}} \bar{X}_i^{v,1} \right\|. \quad (2)$$

To handle the scale ambiguity between prediction and ground-truth, we normalize the predicted and ground-truth pointmaps by scaling factors $z = \text{norm}(X^{1,1}, X^{2,1})$ and $\bar{z} = \text{norm}(\bar{X}^{1,1}, \bar{X}^{2,1})$, respectively, which simply represent the average distance of all valid points to the origin:

$$\text{norm}(X^1, X^2) = \frac{1}{|\mathcal{D}^1| + |\mathcal{D}^2|} \sum_{v \in \{1,2\}} \sum_{i \in \mathcal{D}^v} \|X_i^v\|. \quad (3)$$

Confidence-aware loss. In reality, and contrary to our assumption, there are ill-defined 3D points, e.g. in the sky or on translucent objects. More generally, some parts in the image are typically harder to predict than others. We thus jointly learn to predict a score for each pixel which represents the confidence that the network has about this particular pixel. The final training objective is the confidence-weighted regression loss from Eq. (2) over all valid pixels:

$$\mathcal{L}_{\text{conf}} = \sum_{v \in \{1,2\}} \sum_{i \in \mathcal{D}^v} C_i^{v,1} \ell_{\text{regr}}(v, i) - \alpha \log C_i^{v,1} \quad (4)$$

regularization term $\rightarrow Q7$

where $C_i^{v,1}$ is the confidence score for pixel i , and α is a hyper-parameter controlling the regularization term [17]. To ensure a strictly positive confidence, we typically define $C_i^{v,1} = 1 + \exp c_i^{v,1} \gg 0$, with $c_i^{v,1} \in \mathbb{R}$. This has the effect of forcing the network to extrapolate in harder areas, e.g. those ones covered by a single view. Training network f with this objective allows to estimate confidence scores without an explicit supervision. Examples of input image pairs with their corresponding outputs are shown in Fig. 3 and in the supplementary in Figs. 1, 2 and 5.

$C_i^{v,1}$ low, quickly increase, X
 ensure high confidence $\rightarrow C_i^{v,1}$ high \rightarrow (regression) focus on

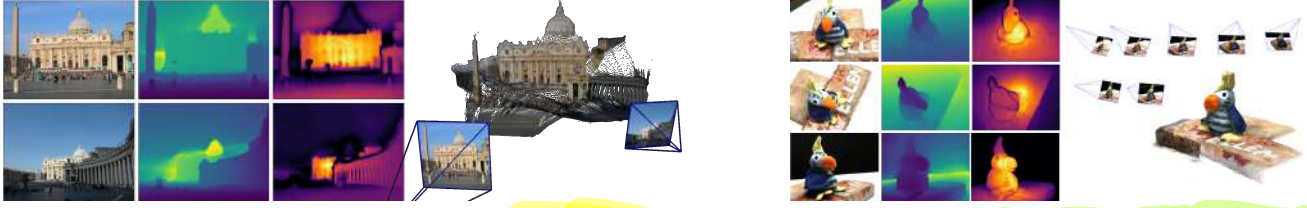


Figure 3. **Reconstruction examples** on two scenes never seen during training. From left to right: RGB, depth map, confidence map, reconstruction. The left scene shows the raw result output from $f(I^1, I^2)$. The right scene shows the outcome of global alignment (Sec. 3.4).

3.3. Downstream Applications

It is also a pre-trained model

The rich properties of the output pointmaps allows us to perform various convenient operations with relative ease.

Point matching. Establishing correspondences between pixels of two images can be trivially achieved by nearest neighbor (NN) search in the 3D pointmap space. To minimize errors, we typically retain reciprocal (mutual) correspondences $\mathcal{M}_{1,2}$ between images I^1 and I^2 , i.e. we have:

$$\mathcal{M}_{1,2} = \{(a, b) \mid a = \text{NN}^{1,2}(b) \text{ and } b = \text{NN}^{2,1}(a)\}$$

$$\text{with } \text{NN}^{n,m}(a) = \arg \min_{b \in \{0, \dots, WH\}} \|X_b^{n,1} - X_a^{m,1}\|.$$

Recovering intrinsics. By definition, the pointmap $X^{1,1}$ is expressed in I^1 's coordinate frame. It is therefore possible to estimate the camera intrinsic parameters by solving a simple optimization problem. In this work, we assume that the principal point is approximately centered and pixels are squares, hence only the focal f_1^* remains to be estimated:

$$f_1^* = \arg \min_{f_1} \sum_{i=0}^W \sum_{j=0}^H C_{i,j}^{1,1} \left\| (i', j') - f_1 \frac{(X_{i,j,0}^{1,1}, X_{i,j,1}^{1,1})}{X_{i,j,2}^{1,1}} \right\|,$$

with $i' = i - \frac{W}{2}$ and $j' = j - \frac{H}{2}$. Fast iterative solvers, e.g. based on the Weiszfeld algorithm [71], can find the optimal f_1^* in a few iterations. For the focal f_2^* of the second camera, the simplest option is to perform the inference for the pair (I^2, I^1) and use above formula with $X^{2,2}$ instead of $X^{1,1}$.

Relative pose estimation can be achieved in several fashions. One way is to perform 2D matching and recover intrinsics as described above, then estimate the Epipolar matrix and recover the relative pose [40]. Another, more direct way is to compare the pointmaps $X^{1,1} \leftrightarrow X^{1,2}$ (or, equivalently, $X^{2,2} \leftrightarrow X^{1,2}$) using Procrustes alignment [54] to get the scaled relative pose $P^* = \sigma^*[R^*|t^*]$:

$$P^* = \arg \min_{\sigma, R, t} \sum_i C_i^{1,1} C_i^{1,2} \left\| \sigma(RX_i^{1,1} + t) - X_i^{1,2} \right\|^2,$$

which can be achieved in closed-form. Procrustes alignment is, unfortunately, sensitive to noise and outliers. A more robust solution is to rely on RANSAC [29] with PnP [40, 44].

Absolute pose estimation, also termed visual localization, can likewise be achieved in several different ways. Let I^Q denote the query image and I^B the reference image for

which 2D-3D correspondences are available. First, intrinsics for I^Q can be estimated from $X^{Q,Q}$ as explained above. Then, one possibility is to run PnP-RANSAC [29, 44] from 2D pixel correspondences obtained between I^Q and some I^B , which in turn yields 2D-3D correspondences for I^Q . Another solution is to get the relative pose between I^Q and I^B as described previously. Then, we convert this pose to world coordinate by scaling it appropriately, according to the scale between $X^{B,B}$ and the ground-truth pointmap for I^B .

3.4. Global Alignment

purpose

The network f presented so far can only handle a pair of images. We now present a fast and simple post-processing optimization for larger scenes. It enables the alignment of pointmaps predicted from multiple images into a joint 3D space. This is possible thanks to the rich content of our pointmaps, which encompasses by design two aligned point-clouds and their corresponding pixel-to-3D mapping.

Pairwise graph. Given a set of images $\{I^1, I^2, \dots, I^N\}$ for a given scene, we first construct a connectivity graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ where N images form vertices \mathcal{V} and each edge $e = (n, m) \in \mathcal{E}$ indicates that images I^n and I^m share some visual content. To that aim, we either use existing off-the-shelf image retrieval methods, or we pass all pairs through network f (inference takes ≈ 25 ms on a H100 GPU) to measure their overlap from the average confidence in both pairs, and then filter out low-confidence pairs.

Global optimization. We use the connectivity graph \mathcal{G} to recover globally aligned pointmaps $\{\chi^n \in \mathbb{R}^{W \times H \times 3}\}$ for all cameras $n = 1 \dots N$. To that aim, we first predict, for each image pair $e = (n, m) \in \mathcal{E}$, the pairwise pointmaps $X^{n,n}$, $X^{m,n}$ and their associated confidence maps $C^{n,n}$, $C^{m,n}$. For the sake of clarity, let us define $X^{n,e} := X^{n,n}$ and $X^{m,e} := X^{m,n}$. Since our goal involves to express all pairwise predictions in a common coordinate frame, we introduce a pairwise pose $P_e \in \mathbb{R}^{3 \times 4}$ and scaling $\sigma_e > 0$ associated to each pair $e \in \mathcal{E}$. We then formulate the following optimization problem:

$$\chi^* = \arg \min_{\chi, P, \sigma} \sum_{e \in \mathcal{E}} \sum_{v \in e} \sum_{i=1}^{HW} C_i^{v,e} \|\chi_i^v - \sigma_e P_e X_i^{v,e}\|. \quad (5)$$

Here, with some abuse of notation, we write $v \in e$ for $v \in \{n, m\}$ if $e = (n, m)$. The idea is that, for a given pair e , the same rigid transformation P_e should align both pointmaps

$X^{n,e}$ and $X^{m,e}$ with the world-coordinate pointmaps χ^n and χ^m , since $X^{n,e}$ and $X^{m,e}$ are by definition both expressed in the same coordinate frame. To avoid the trivial optimum where $\sigma_e = 0$, $\forall e \in \mathcal{E}$, we enforce that $\prod_e \sigma_e = 1$.

Recovering camera parameters. A straightforward extension to this framework enables to recover all cameras parameters. By simply replacing $\chi_{i,j}^n := P_n^{-1}h(K_n^{-1}D_{i,j}^n[i, j, 1]^\top)$ (i.e. enforcing a standard camera pinhole model as in Eq. (1)), we can thus estimate all camera poses $\{P_n\}$, associated intrinsics $\{K_n\}$ and depthmaps $\{D^n\}$ for $n = 1 \dots N$. To accelerate convergence, we initialize all parameters using pairwise relative pose estimates propagated along a maximum spanning tree of \mathcal{G} , see Sec. G of the supplementary.

Discussion. We point out that, contrary to traditional bundle adjustment, this global optimization is fast and simple to perform in practice. Indeed, we are not minimizing 2D reprojection errors, as bundle adjustment normally does, but 3D projection errors. The optimization is carried out using standard gradient descent and typically converges after a few hundred steps, requiring mere seconds on a standard GPU.

4. Experiments with DUST3R

Training data. We train our network with a mixture of eight datasets: Habitat [82], MegaDepth [47], ARKitScenes [22], Static Scenes 3D [56], Blended MVS [122], ScanNet++ [126], CO3D-v2 [75] and Waymo [94]. These datasets feature diverse scene types: indoor, outdoor, landmarks, synthetic, real-world, object-centric, etc. When image pairs are not directly provided with the dataset, we extract them based on the method described in [113]. Specifically, we utilize off-the-shelf image retrieval and point matching algorithms to match and verify image pairs. All in all, we extract 8.5M pairs in total.

Training details. During each epoch, we randomly sample an equal number of pairs from each dataset to compensate disparities in dataset sizes. We wish to feed relatively high-resolution images to our network, say 512 pixels in the largest dimension. To mitigate the high cost associated with such input, we train our network sequentially, first on 224×224 images and then on larger 512-pixel images. We randomly select the image aspect ratios for each batch (e.g. 16/9, 4/3, etc), so that at test time our network is familiar with different image shapes. We crop images to the desired aspect-ratio, and resize the largest dimension to 512 pixels.

We use standard data augmentation techniques and training set-up overall. Our network architecture comprises a ViT-Large for the encoder [25], a ViT-Base for the decoder, both with patches of 16×16 pixels, and a DPT head [73]. We refer to the supplementary in Sec. H for more details on the training and architecture. Before training, we initialize our network with the weights of an off-the-shelf CroCo pretrained model [114]. Cross-View completion (CroCo) is a recently proposed pretraining paradigm inspired by MAE [41] that

has been shown to excel on various downstream 3D vision tasks [113], and is thus particularly suited to our framework.

Evaluation. In the remainder of this section, we benchmark DUST3R on a representative set of classical 3D vision tasks, each time specifying datasets, metrics and comparing performance with existing state-of-the-art approaches. We emphasize that all results are obtained with the *same* DUST3R model (our default model is denoted as ‘DUST3R 512’, other DUST3R models serve for the ablations in Sec. F of the suppl.), i.e. we never finetune our model on a particular downstream task (zero-shot settings). During test, all images are rescaled to 512 pixels while preserving their aspect ratio. Since there may exist different ‘routes’ to extract task-specific outputs from DUST3R, as described in Sec. 3.3 and Sec. 3.4, we precise each time the employed method.

Recovering intrinsics with DUST3R is possible in monocular and binocular settings, see Sec. E of the supplementary.

Qualitative results. As shown in Fig. 1, DUST3R yields high-quality dense 3D reconstructions even in challenging situations. It can even *reconstruct scenes for which images share no visual overlap* (top-right office example). We refer the reader to the supplementary in Sec. A for more visualizations of pairwise and multi-view reconstructions.

4.1. Map-free Visual Localization

Dataset. We experiment with the Map-free relocalization benchmark [2], an extremely challenging test-bed where the goal is to localize the camera in metric space given a single reference image (i.e. without any map). The benchmark comprises a training set which we do not use at all, 65 validation and 130 test scenes. For each scene, the pose of every frame in a video clip must be independently estimated w.r.t. a single reference image. The video clip is captured with a different device at a different moment (possibly months before or after the reference image), and the ground-truth is privately held-out, making the benchmark as fair as possible.

Protocol. The evaluation returns absolute camera pose accuracy (localization thresholds of 5° , 25cm) and Virtual Correspondence Reprojection Error (VCRE) measured as the average Euclidean distance of the reprojection errors of virtual 3D points projected according to ground truth and estimated camera poses. To evaluate DUST3R, we first extract pixel correspondences as described in Section 3.3 of the main paper, then we estimate the relative camera pose using RANSAC via the essential matrix using the provided benchmark code. To find the metric scale of the scene, we leverage metric depth from an off-the-shelf DPT-KITTI again using the provided code, similarly to most other methods like RoMa [28], LoFTR [92] and SuperPoint-SuperGlue [23, 81].

Results. Comparisons with the state of the art on the privately held-out test set are reported in Tab. 1. Overall, DUST3R outperforms all state-of-the-art approaches, sometimes by a large margin, achieving less than 1 meter of

		VCRE (< 90px)			Pose Error (< 25cm and 5°)			
	depth	Reproj. ↓	Prec. ↑	AUC ↑	Median Error ↓	Precision ↑	AUC ↑	
RPR [2]	DPT	147.1 px	40.2%	0.402	1.68m	22.5°	6.0%	0.060
SIFT [53]	DPT	222.8 px	25.0%	0.504	2.93m	61.4°	10.3%	0.252
SP+SG [81]	DPT	160.3 px	36.1%	0.602	1.88m	25.4°	16.8%	0.346
LoFTR [92]	DPT	166.7 px	33.4%	0.618	2.31m	39.4°	9.8%	0.269
LoFTR [92]	KBR	165.0 px	34.3%	0.634	2.23m	37.8°	11.0%	0.295
RoMa [28]	DPT	128.8 px	45.6%	0.669	1.23m	11.1°	22.8%	0.407
FAR [79]	(auto)	137.0 px	44.2%	0.680	1.48m	17.2°	17.7%	0.392
DUST3R	DPT	115.8 px	50.3%	0.697	0.98m	7.1°	21.4%	0.393

Table 1. Comparison with the state of the art on the test set of the Map-free benchmark [2]. Methods are ranked by VCRE AUC.

median translation error, whereas other approaches usually achieve between 1.5 and 2.5 meters in median translation error. In terms of reprojection error, DUST3R achieves more than 50% precision at 90 pixel threshold and almost 70% in AUC, which is again far better than most other approaches, including RoMa [28] which relies on the powerful DINOv2 pretraining [62]. It thus appears that correspondences output by DUST3R are more robust than ones by existing matching methods, even though these methods are explicitly designed and trained for matching, whereas DUST3R is not. Indeed, we point out that pixel correspondences are only one of many by-products of our proposed reconstruction framework.

4.2. Multi-view Pose Estimation

We evaluate DUST3R for the task of multi-view relative pose estimation, with and without global alignment (Sec. 3.4).

Datasets. Following [104], we use two multi-view datasets, CO3Dv2 [75] and RealEstate10k [140] for the evaluation. CO3Dv2 contains 6 million frames extracted from approximately 37k videos, covering 51 MS-COCO categories. The ground-truth camera poses are annotated using COLMAP from 200 frames in each video. RealEstate10k is an indoor/outdoor dataset with 10 million frames from about 80K video clips on YouTube, the camera poses being obtained by SLAM with bundle adjustment. We follow the protocol introduced in [104] to evaluate DUST3R on 41 categories from CO3Dv2 and 1.8K video clips from the test set of RealEstate10k. For each sequence, we random select 10 frames and feed all possible 45 pairs to DUST3R.

Baselines and metrics. We compare DUST3R pose estimation results, obtained either from PnP-RANSAC or global alignment, against the learning-based RelPose [135], PoseReg [104] and PoseDiffusion [104], and structure-based PixSFM [50], COLMAP+SPSG (COLMAP [84] extended with SuperPoint [23] and SuperGlue [81]). Similar to [104], we report the Relative Rotation Accuracy (RRA) and Relative Translation Accuracy (RTA) for each image pair to evaluate the relative pose error and select a threshold $\tau = 15$ to report RTA@15 and RRA@15. Additionally, we calculate the mean Average Accuracy (mAA)@30, defined as the area under the curve accuracy of the angular differences at $\min(\text{RRA}@30, \text{RTA}@30)$.

Results. As shown in Table 2, DUST3R with global alignment (GA) achieves the best overall performance on the two datasets and significantly outperforms the state-of-the-art PoseDiffusion [104]. Moreover, DUST3R with PnP also demonstrates superior performance over both learning and structure-based existing methods. It is worth noting that RealEstate10K results reported for PoseDiffusion are from the model trained on CO3Dv2. Nevertheless, we assert that our comparison is justified considering that RealEstate10K is not used either during DUST3R’s training. We also report performance with less input views (between 3 and 10) in the supplementary (Sec. C), in which case DUST3R also yields excellent performance on both benchmarks.

4.3. Monocular Depth

For this monocular task, we simply feed the same input image I to the network as $f(I, I)$. By design, depth prediction is simply the z coordinate in the predicted 3D pointmap.

Datasets and metrics. We benchmark DUST3R on two outdoor (DDAD [38], KITTI [34]) and three indoor (NYUv2 [89], BONN [64], TUM [91]) datasets. We compare DUST3R’s performance to state-of-the-art methods categorized in supervised, self-supervised and zero-shot settings, this last category corresponding to DUST3R. We use two metrics commonly used for monocular depth evaluations [6, 90]: the absolute relative error $AbsRel$ between target y and prediction \hat{y} , $AbsRel = |y - \hat{y}|/y$, and the prediction threshold accuracy, $\delta_{1.25} = \max(\hat{y}/y, y/\hat{y}) < 1.25$.

Results. In zero-shot setting, the state of the art is represented by the recent SlowTv [90]. This approach collected a large mixture of curated datasets with urban, natural, synthetic and indoor scenes, and trained one common model. For every dataset in the mixture, camera parameters are known or estimated with COLMAP. As Table 2 shows, DUST3R adapts well to outdoor and indoor environments. It outperforms the self-supervised baselines [6, 36, 93] and performs on-par with SoTA supervised baselines [73, 132].

4.4. Multi-view Depth

We evaluate DUST3R for the task of multi-view stereo depth estimation. Likewise, we extract depthmaps as the z -coordinate of predicted pointmaps. In the case where multiple depthmaps are available for the same image, we rescale all predictions to align them together and aggregate all predictions via a simple averaging weighted by the confidence.

Datasets and metrics. Following [86], we evaluate it on the DTU [1], ETH3D [85], Tanks and Temples [43], and ScanNet [20] datasets. We report the Absolute Relative Error (rel) and Inlier Ratio (τ) with a threshold of 1.03 on each test set, and the averages across all test sets. Note that we do not leverage the ground-truth camera parameters and poses nor the ground-truth depth ranges, so our predictions are only valid up to a scale factor. In order to perform

Methods	Train	Outdoor				Indoor							
		DDAD[38]		KITTI [34]		BONN [64]		NYUD-v2 [89]		TUM [91]			
		Rel↓	$\delta_{1.25}\uparrow$	Rel↓	$\delta_{1.25}\uparrow$	Rel↓	$\delta_{1.25}\uparrow$	Rel↓	$\delta_{1.25}\uparrow$	Rel↓	$\delta_{1.25}\uparrow$	Rel↓	$\delta_{1.25}\uparrow$
DPT-BEiT[73]	D	10.70	84.63	9.45	89.27	-	-	5.40	96.54	10.45	89.68		
NeWCRFs[132]	D	9.59	82.92	5.43	91.54	-	-	6.22	95.58	14.63	82.95		
Monodepth2 [36]	SS	23.91	75.22	11.42	86.90	56.49	35.18	16.19	74.50	31.20	47.42		
SC-SfM-Learners [6]	SS	16.92	77.28	11.83	86.61	21.11	71.40	13.79	79.57	22.29	64.30		
SC-DepthV3 [93]	SS	14.20	81.27	11.79	86.39	12.58	88.92	12.34	84.80	16.28	79.67		
MonoViT[138]	SS	-	-	09.92	90.01	-	-	-	-	-	-		
RobustMIX [74]	T	-	-	18.25	76.95	-	-	11.77	90.45	15.65	86.59		
SlowTv [90]	T	12.63	79.34	(6.84)	(56.17)	-	-	11.59	87.23	15.02	80.86		
DUS3R 224-NoCroCo	T	19.63	70.03	20.10	71.21	14.44	86.00	14.51	81.06	22.14	66.26		
DUS3R 224	T	16.32	77.58	16.97	77.89	11.05	89.95	10.28	88.92	17.61	75.44		
DUS3R 512	T	13.88	81.17	10.74	86.60	8.08	93.56	6.50	94.09	14.17	79.89		

Table 2. **Left:** Monocular depth estimation on multiple benchmarks. D-Supervised, SS-Self-supervised, T-transfer (zero-shot). (Parentheses) refers to training on the same set. **Right:** Multi-view pose regression on the CO3Dv2 [75] and RealEst10K [140] with 10 random frames.

Methods	GT	GT	GT	Align	KITTI		ScanNet		ETH3D		DTU		T&T		Average	
					rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$ time (s)↓
					rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$	rel↓	$\tau\uparrow$ time (s)↓
(a) COLMAP [83, 84]	✓	×	✓	×	12.0	58.2	14.6	34.2	16.4	55.1	0.7	96.5	2.7	95.0	9.3	67.8 \approx 200
COLMAP Dense [83, 84]	✓	×	✓	×	26.9	52.7	38.0	22.5	89.8	23.2	20.8	69.3	25.7	76.4	40.2	48.8 \approx 200
MVSNet [121]	✓	×	✓	×	22.7	36.1	24.6	20.4	35.4	31.4	(1.8)	(86.0)	8.3	73.0	18.6	49.4 0.07
(b) MVSNInv. Depth [121]	✓	✓	✓	×	18.6	30.7	22.7	20.9	21.6	35.6	(1.8)	(86.7)	6.5	74.6	14.2	49.7 0.32
Vis-MVSSNet [134]	✓	✓	✓	×	9.5	55.4	8.9	33.5	10.8	43.3	(1.8)	(87.4)	4.1	87.2	7.0	61.4 0.70
DeMon [102]	✓	×	✓	×	16.7	13.4	75.0	0.0	19.0	16.2	23.7	11.5	17.6	18.3	30.4	11.9 0.08
DeepV2D KITTI [98]	✓	×	✓	×	(20.4)	(16.3)	25.8	8.1	30.1	9.4	24.6	8.2	38.5	9.6	27.9	10.3 1.43
DeepV2D ScanNet [98]	✓	×	✓	×	61.9	5.2	(3.8)	(60.2)	18.7	28.7	9.2	27.4	33.5	38.0	25.4	31.9 2.15
(c) MVSNet [121]	✓	×	✓	×	14.0	35.8	1568.0	5.7	507.7	8.3	(4429.1)	(0.1)	118.2	50.7	1327.4	20.1 0.15
MVSNInv. Depth [121]	✓	×	✓	×	29.6	8.1	65.2	28.5	60.3	5.8	(28.7)	(48.9)	51.4	14.6	47.0	21.2 0.28
Vis-MVSSNet [134]	✓	×	✓	×	10.3	54.4	84.9	15.6	51.5	17.4	(374.2)	(1.7)	21.1	65.6	108.4	31.0 0.82
RobustMVD Baseline [86]	✓	×	✓	×	7.1	41.9	7.4	38.4	9.0	42.6	2.7	82.0	5.0	75.1	6.3	56.0 0.06
DeMoN [102]	×	×	✓	t	15.5	15.2	12.0	21.0	17.4	15.4	21.8	16.6	13.0	23.2	16.0	18.3 0.08
DeepV2D KITTI [98]	×	×	✓	med	(3.1)	(74.9)	23.7	11.1	27.1	10.1	24.8	8.1	34.1	9.1	22.6	22.7 2.07
DeepV2D ScanNet [98]	×	×	✓	med	10.0	36.2	(4.4)	(54.8)	11.8	29.3	7.7	33.0	8.9	46.4	8.6	39.9 3.57
(d) DUS3R 224-NoCroCo	×	×	×	med	15.14	21.16	7.54	40.00	9.51	40.07	3.56	62.83	11.12	37.90	9.37	40.39 0.05
DUS3R 224	×	×	×	med	15.39	26.69	(5.86)	(50.84)	4.71	61.74	2.76	77.32	5.54	56.38	6.85	54.59 0.05
DUS3R 512	×	×	×	med	9.11	39.49	(4.93)	(60.20)	2.91	76.91	3.52	69.33	3.17	76.68	4.73	64.52 0.13

Table 3. **Left:** Multi-view depth evaluation with different settings: a) Classical approaches; b) with poses and depth range, without alignment; c) absolute scale evaluation with poses, without depth range and alignment; d) without poses and depth range, but with alignment. (Parentheses) denote training on data from the same domain. The best results for each setting are in **bold**. **Right:** MVS results on the DTU dataset, in *mm*. Traditional handcrafted methods (a) have been overcome by learning-based approaches (b) that train on this specific domain.

quantitative measurements, we thus normalize predictions using the medians of the predicted depths and the ground-truth ones, as advocated in [86].

Results. We observe in Tab. 3 (left) that DUS3R achieves state-of-the-art accuracy on ETH-3D and outperforms most recent state-of-the-art methods overall, even those using ground-truth camera poses. Time-wise, our approach is also much faster than the traditional COLMAP pipeline [83, 84]. This showcases the applicability of our method on a large variety of domains, either indoors, outdoors, small scale or large scale scenes, while not having been trained on the test domains, except for the ScanNet test set, since the train split is part of our Habitat dataset. We additionally provide the comparison with other baselines in Tab. 7 of supplementary.

4.5. 3D Reconstruction

Finally, we measure the quality of our full reconstructions obtained after the global alignment procedure described in Sec. 3.4. We again emphasize that our method is the first one to enable global unconstrained MVS, in the sense that we have no prior knowledge regarding the camera parameters. In order to quantify the quality of our reconstructions, we simply align the predictions to the ground-truth coordinate system. This is done by fixing the parameters as constants in Eq. (5). This leads to consistent 3D reconstructions expressed in the coordinate system of the ground-truth.

Datasets and metrics. We evaluate our predictions on the

Methods	Co3Dv2			RealEstate10K
	RRA@15	RTA@15	mAA(30)	mAA(30)
RelPose [135]	57.1	-	-	-
Colmap+SPSG [23, 81]	36.1	27.3	25.3	45.2
PixSfM [50]	33.7	32.9	30.1	49.4
PosReg [104]	53.2	49.1	45.0	-
PoseDiffusion [104]	80.5	79.8	66.5	48.0
DUS3R 512 (w/ PnP)	94.3	88.4	77.2	61.2
DUS3R 512 (w/ GA)	96.2	86.8	76.7	67.7

Methods	GT cams	Acc.↓	Comp.↓	Overall↓
(a) Camp [11]	✓	0.835	0.554	0.695
Furu [32]	✓	0.613	0.941	0.777
Tola [100]	✓	0.342	1.190	0.766
Gipuma [33]	✓	0.283	0.873	0.578
(b) MVSNet [121]	✓	0.396	0.527	0.462
CVP-MVSNet [119]	✓	0.296	0.406	0.351
UCS-Net [16]	✓	0.338	0.349	0.344
CER-MVS [55]	✓	0.359	0.305	0.332
CIDER [118]	✓	0.417	0.437	0.427
PatchmatchNet [103]	✓	0.427	0.277	0.352
GeoMVSNet [136]	✓	0.331	0.259	0.295
DUS3R 512	×	2.677	0.805	1.741

DTU [1] dataset. We apply our network in a zero-shot setting, *i.e.* we do not finetune on the DTU train set and apply our model as is. In Tab. 3 (right) we report the averaged accuracy, averaged completeness and overall averaged error metrics as provided by the authors of the benchmarks. The accuracy for a point of the reconstructed shape is defined as the smallest Euclidean distance to the ground-truth, and the completeness of a point of the ground-truth as the smallest Euclidean distance to the reconstructed shape. The overall is simply the mean of both previous metrics.

Results. Our method does not reach the accuracy levels of the best methods. In our defense, these methods all leverage GT poses and train specifically on the DTU train set whenever applicable. Furthermore, best results on this task are usually obtained via sub-pixel accurate triangulation, requiring the use of explicit camera parameters, whereas our approach relies on regression, which is known to be less accurate. Yet, without prior knowledge about the cameras, we reach an average accuracy of 2.7mm, with a completeness of 0.8mm, for an overall average distance of 1.7mm. We believe this level of accuracy to be of great use in practice, considering the *plug-and-play* nature of our approach.

5. Conclusion

We presented a novel paradigm to solve not only 3D reconstruction in-the-wild without prior information about scene nor cameras, but a whole variety of 3D vision tasks as well.

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