Dense Object Nets: Learning Dense Visual Object Descriptors By and For Robotic Manipulation

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Abstract:
What is the right object representation for manipulation? We would like robots to visually perceive scenes and learn an understanding of the objects in them that (i) is task-agnostic and can be used as a building block for a variety of manipulation tasks, (ii) is generally applicable to both rigid and non-rigid objects, (iii) takes advantage of the strong priors provided by 3D vision, and (iv) is entirely learned from self-supervision. This is hard to achieve with previous methods: much recent work in grasping does not extend to grasping specific objects or other tasks, whereas task-specific learning may require many trials to generalize well across object configurations or other tasks. In this paper we present Dense Object Nets, which build on recent developments in self-supervised dense descriptor learning, as a consistent object representation for visual understanding and manipulation. We demonstrate they can be trained quickly (approximately 20 minutes) for a wide variety of previously unseen and potentially non-rigid objects. We additionally present novel contributions to enable multi-object descriptor learning, and show that by modifying our training procedure, we can either acquire descriptors which generalize across classes of objects, or descriptors that are distinct for each object instance. Finally, we demonstrate the novel application of learned dense descriptors to robotic manipulation. We demonstrate grasping of specific points on an object across potentially deformed object configurations, and demonstrate using class general descriptors to transfer specific grasps across objects in a class.

Keywords: Visual Descriptor Learning, Self-Supervision, Robot Manipulation

1 Introduction
What is the right object representation for manipulation? While task-specific reinforcement learning can achieve impressively dexterous skills for a given specific task [1], it is unclear which is the best route to efficiently achieving many different tasks. Other recent work [2, 3] can provide very general grasping functionality but does not address specificity. Achieving specificity, the ability to accomplish specific tasks with specific objects, may require solving the data association problem. At a coarse level the task of identifying and manipulating individual objects can be solved by semantic segmentation, as demonstrated in the Amazon Robotics Challenge (ARC) [4, 5] or [6]. However, the representation provided by semantic segmentation does not provide any information on the rich structure of the objects themselves, and hence may not be an appropriate representation for solving complex tasks beyond the pick and place scenario of the ARC.

Moving beyond visual segmentation, recent work [7] marks an advance in learning dense pixel level data association using self-supervision from raw RGBD data. We have been inspired by [7] but we required additional innovations to reliably learn consistent object descriptors and develop a learning method suitable for automation by a robot. Additionally, no prior work has: investigated object uniqueness of dense descriptors, demonstrated dense description learning for more than just a single class of objects, or investigated using dense descriptors for manipulation tasks. In this paper we introduce Dense Object Nets, which are deep neural networks trained to provide dense (pixelwise) description of objects. Dense Object Nets can distinguish multiple objects, be quickly learned in an entirely robotic self-supervised fashion, and enable new manipulation tasks.

Video and source code available at https://youtu.be/L5UW1VapKNK and https://github.com/RobotLocomotion/pytorch-dense-correspondence.
Contributions. We believe our largest contribution is that we introduce robotic learning of dense descriptors for objects and show its broad applicability and usefulness for robotic manipulation. A primary contribution is the novel development of multi-object distinct dense descriptors, for which we introduce three methods for acquiring them: cross-object loss, direct multi-object training, and synthetic multi-object training. We show that by modifying the loss function and sampling procedure, we can either acquire descriptors which generalize across classes of objects, or descriptors that are distinct for each object instance. Additionally, we’ve demonstrated that robotic self-supervised dense visual descriptor learning can be applied to a wide variety of potentially non-rigid objects and classes (47 objects so far, including 3 distinct classes), and can be learned quickly (approximately 20 minutes). We also contribute general training techniques for learning dense descriptors (Section 3.2) which we found to be critical to achieving good performance in practice. Finally, we demonstrate the novel application of learned dense descriptors to robotic manipulation. In example tasks we grasp specific points on objects across potentially deformed configurations, do so with object instance-specificity in clutter, or transfer specific grasps across objects in a class.

2 Related Work

We review three main areas of related work: learned descriptors, self-supervised visual learning for robots, and robot learning for specific tasks. In the area of learned visual descriptors our method builds on the approach of Schmidt et al. [7]. Relative to [7] we contribute distinct multi-object descriptors, new training procedures, a robotic automated collection pipeline, and demonstrate applications to robotic manipulation. Other work [8] uses image warping to learn 3 dimensional dense descriptors for a dataset of celebrity faces, and shows the learned descriptors are consistent across faces. A thorough comparison to other related work in the area of learned descriptors is provided in [7], but we provide a brief summary here. Most work on learning dense correspondences [9, 10, 11] requires absolute labels which must be annotated manually. [12, 13, 14] use relative labels to train patch-based, rather than dense, feature descriptors, and rely on global alignment of all known patches. Zeng et al. [15] also uses generative model based dense 3D reconstructions to provide automated labeling, but for descriptors of 3D volume patches. Our work, along with [7, 8, 11], learn descriptors for specific object instances or classes, while [15] learns a local volumetric patch descriptor for establishing correspondences between arbitrary partial 3D data.

In the area of self-supervised visual robot learning, while some recent work has sought to understand ‘how will the world change given the robot’s action?’ [16, 17] in this work we instead ask “what is the current visual state of the robot’s world?”. We address this question with a dense description that is consistent across viewpoints, object configurations and (if desired) object classes. At the coarse level of semantic segmentation several works from the Amazon Robotics Challenge used robots to automate the data collection and annotation process through image-level background subtraction [18, 5, 4]. In contrast this work uses 3D reconstruction-based change detection and dense pixelwise correspondences, which provides a much richer supervisory signal for use during training.

In the area of robot learning for a specific task there have been impressive works on end-to-end reinforcement learning [1, 19]. In these papers the goal is to learn a specific task, encoded with a reward function, whereas we learn a general task agnostic visual representation. There have also been several works focusing on grasping from RGB or depth images [3, 18, 2, 20]. These papers focus on successfully grasping any item out of a pile, and are effectively looking for graspable features. They have no consistent object representation or specific location on that object, and thus the robotic manipulation tasks we demonstrate in Section 5.4, e.g. grasping specific points on an object across potentially deformed object configurations, are out of scope for these works.

3 Methodology

As preliminary in Section 3.1 we describe the general technique for self-supervising dense visual descriptor learning, which is from [7] but reproduced here for clarity. Sections 3.2, 3.3, and 4 are contributions of this paper. In Section 3.2 we describe techniques we’ve developed for object-centric descriptors, and 3.3 describes techniques for distinct multi-object descriptors. Section 4 describes our experimental setup.

3.1 Preliminary: Self-Supervised Pixelwise Contrastive Loss

We use self-supervised pixelwise contrastive loss, developed in [7]. This learns a dense visual descriptor mapping which maps a full-resolution RGB image, $\mathbb{R}^{W \times H \times 3}$, to a descriptor space, $\mathbb{R}^{W \times H \times D}$.
where for each pixel we have a $D$-dimensional descriptor vector. Training is performed in a Siamese fashion, where a pair of RGB images, $I_a$ and $I_b$ are sampled from one RGBD video, and many pixel matches and non-matches are generated from the pair of images. A pixel $u_a \in \mathbb{R}^2$ from image $I_a$ is a match with pixel $u_b$ from image $I_b$ if they correspond to the same vertex of the dense 3D reconstruction (Figure 1 (c-f)). The dense descriptor mapping is trained via pixelwise contrastive loss. The loss function aims to minimize the distance between descriptors corresponding to a match, while descriptors corresponding to a non-match should be at least a distance $M$ apart, where $M$ is a margin parameter. The dense descriptor mapping $f(\cdot)$ is used to map an image $I \in \mathbb{R}^{W \times H \times 3}$ to descriptor space $f(I) \in \mathbb{R}^{W \times H \times D}$. Given a pixel $u$ we use $f(I)(u)$ to denote the descriptor corresponding to pixel $u$ in image $I$. We simply round the real-valued pixel $u \in \mathbb{R}^2$ to the closest discrete pixel value $u \in \mathbb{N}^2$, but any continuously-differentiable interpolation can be used for sub-pixel resolution. We denote $D(\cdot)$ as the $L_2$ distance between a pair of pixel descriptors: $D(I_a,u_a,I_b,u_b) \triangleq ||f(I_a)(u_a) - f(I_b)(u_b)||_2$. At each iteration of training, a large number (on the order of 1 million total) of matches $N_{\text{matches}}$ and non-matches $N_{\text{non-matches}}$ are generated between images $I_a$ and $I_b$. The images are mapped to corresponding descriptor images via $f(\cdot)$ and the loss function is

$$L_{\text{matches}}(I_a,I_b) = \frac{1}{N_{\text{matches}}} \sum_{N_{\text{matches}}} D(I_a,u_a,I_b,u_b)^2$$

$$L_{\text{non-matches}}(I_a,I_b) = \frac{1}{N_{\text{non-matches}}} \sum_{N_{\text{non-matches}}} \max(0,M - D(I_a,u_a,I_b,u_b))^2$$

$$L(I_a,I_b) = L_{\text{matches}}(I_a,I_b) + L_{\text{non-matches}}(I_a,I_b)$$

### 3.2 Training Procedures for Object-Centric Descriptors

Prior work [7] has used dynamic reconstruction [21] of raw RGBD data for only within-scene data association and remarkably showed that even without cross-scene data association, descriptors could be learned that were consistent across many dynamic scenes of the upper body of a human subject. While dynamic reconstruction is powerful, the challenges of topology changes [22] and difficulties of occlusion make it difficult to reliably deploy for an autonomous system. Schmidt et al. [7] also used data associations from static scene reconstructions for the task of relocalization in the same static environment. In contrast we sought to use only static reconstruction but seek consistency for dynamic objects. Other work [8] obtains dense descriptor consistency for a curated dataset of celebrity faces using only image warping for data association.

Using our robot mounted camera we are able to reliably collect high quality dense reconstructions for static scenes. Initially we applied only static-scene reconstruction to learn descriptors for specific objects, but we found that the learned object descriptors were not naturally consistent for challenging datasets with objects in significantly different configurations. Subsequently we developed techniques that leverage 3D reconstruction change detection, data augmentation, and loss function balancing to reliably produce consistent object representations with only static-scene data association for the wide variety of objects we have tested. These techniques also improve the precision of correspondences, as is discussed in Section 5.1. While we have tried many other ideas, these are the techniques that were empirically found to significantly improve performance.

![Figure 1: Overview of the data collection and training procedure. (a) automated collection with a robot arm. (b) change detection using the dense 3D reconstruction. (c)-(f) matches depicted in green, non-matches depicted in red.](image)

**Object masking via 3D change detection.** Since we are trying to learn descriptors of objects that take up only a fraction of a full image, we observe significant improvements if the representational power of the models are focused on the objects rather than the backgrounds. A $640 \times 480$ image contains 307,200 pixels but an image in our dataset may have as few as 1,000 to 10,000 of those pixels, or 3%-5%, that correspond
We of course would like robots to have dense visual models of more than just one object. When we began this work it wasn’t obvious to us what scale of changes to our training procedure or model architecture would be required in order to simultaneously (a) achieve individual single-object performance comparable to a single-object-only model, while also (b) learn dense visual descriptors for objects that are globally distinct – i.e., the bill of a hat would occupy a different place in descriptor space than the handle of a mug. To achieve distinctness, we introduce three strategies:

i. Cross-object loss. The most direct way to ensure that different objects occupy different subsets of descriptor space is to directly impose cross-object loss (Figure 1d). Between two different objects, we know that each and every pair of pixels between them is a non-match. Accordingly we randomly select two images of two different objects, randomly sample many pixels from each object (enabled by object masking), and apply non-match loss (with hard-negative scaling) to all of these pixel pairs.

ii. Direct training on multi-object scenes. A nice property of pixelwise contrastive loss, with data associations provided by 3D geometry, is that we can directly train on multi-object, cluttered scenes without any individual object masks (Figure 1e). This is in contrast with training pixelwise semantic segmentation, which requires labels for each individual object in clutter that may be difficult to attain, i.e. through human labeling. With pixel-level data associations provided instead by 3D geometry, the sampling of matches and the loss function still makes sense, even in clutter.

iii. Synthetic multi-object scenes. We can also synthetically create multi-object scenes by layering object masks [4]. To use dense data associations through synthetic image merging, we prune matches that become occluded during layering (Figure 1f). A benefit of this procedure is that we can create a combinatorial number of “multi-object” scenes from only single object-scenes, and can cover a wide range of occlusion types without collecting physical scenes for each.

Background domain randomization. A strategy to encourage cross-scene consistency is to enforce that the learned descriptors are not reliant on the background. Since we have autonomously acquired object masks, we can domain randomize [25] the background (Figure 1c top) to encourage consistency – rather than memorizing the background (i.e. by describing the object by where it is relative to a table edge), the descriptors are forced to be representative of only the object.

Hard-negative scaling. Although as in [7] we originally normalized \( L_{\text{matches}} \) and \( L_{\text{non-matches}} \) by \( N_{\text{matches}} \) and \( N_{\text{non-matches}} \), respectively, we found that what we call the “hard-negative rate”, i.e. the percentage of sampled non-matches for which \( M - D(I_a,u_a,I_b,u_b) > 0 \) would quickly drop well below 1% during training. While not precisely hard-negative mining [26], we empirically measure improved performance if rather than scaling \( L_{\text{non-matches}} \) by \( N_{\text{non-matches}} \), we adaptively scale by the number of hard negatives in the non-match sampling, \( N_{\text{hard-negatives}} \), where \( I \) is the indicator function:

\[
N_{\text{hard-negatives}} = \sum_{N_{\text{non-matches}}} I(M - D(I_a,u_a,I_b,u_b) > 0) \quad (4)
\]

\[
L_{\text{non-matches}}(I_a,I_b) = \frac{1}{N_{\text{hard-negatives}}} \sum_{N_{\text{non-matches}}} \max(0,M - D(I_a,u_a,I_b,u_b))^2 \quad (5)
\]

Data diversification and augmentation. While we collect only a modest number of scenes (4-10) per object or class, we ensure they are diverse. We physically acquire a diverse set of orientations, crops, and lighting conditions by utilizing the full workspace of our 7-DOF robot arm, randomizing end-effector rotations with an approximate gaze constraint towards the collection table, and varying lighting conditions. We also applied synthetic 180-degree rotations randomly to our images.

3.3 Multi-Object Dense Descriptors

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4 Experimental

Data Collection and Pre-Processing. The minimum requirement for raw data is to collect an RGBD video of an object or objects. Figure 1 shows our experimental setup; we utilize a 7-DOF robot arm (Kuka IIWA LBR) with an RGBD sensor (Primesense Carmine 1.09) mounted at the end-effector. With the robot arm, data collection can be highly automated, and we can achieve reliable camera poses by using forward kinematics along with knowledge of the camera extrinsic calibration. For dense reconstruction we use TSDF fusion [27] of the depth images with camera poses provided by forward kinematics. An alternative route to collecting data which does not require a calibrated robot is to use a dense SLAM method (for example, [28, 29]). In between collecting RGBD videos, the object of interest should be moved to a variety of configurations, and the lighting can be changed if desired. While for many of our data collections a human moved the object between configurations, we have also implemented and demonstrated (see our video) the robot autonomously rearranging the objects, which highly automates the object learning process.

We employ a Schunk two-finger gripper and plan grasps directly on the object point cloud (Appendix C). If multiple different objects are used, currently the human must still switch the objects for the robot and indicate which scenes correspond to which object, but even this information could be automated by the robot picking objects from an auxiliary bin.

Training Dense Descriptors. For training, at each iteration we randomly sample between some subset of specified image comparison types (Single Object Within Scene, Different Object Across Scene, Multi Object Within Scene, Synthetic Multi Object), and then sample some set of matches and non-matches for each. In this work, we use only static-scene reconstructions, so pixel matches between images can be easily found by raycasting and reprojecting against the dense 3D reconstruction model, and appropriately checking for occlusions and field-of-view constraints. For the dense descriptor mapping we train a 34-layer, stride-8 ResNet pretrained on ImageNet, but we expect any fully-convolutional network (FCN) that has shown effectiveness on semantic segmentation tasks to work well. Additional training details are contained in the Appendix D.

5 Results

Objects used
• 47 objects total
• 275 scenes
  • 8 hats
  • 15 shoes
  • 15 mugs
  • 9 additional objects

Figure 2: Learned object descriptors can be consistent across significant deformation (a) and, if desired, across object classes (b-d). Shown for each (a) and (b-d) are RGB frames (top) and corresponding descriptor images (bottom) that are the direct output of a feed-forward pass through a trained network. (e)-(f) shows that we can learn descriptors for low texture objects, with the descriptors masked for clear visualization. Our object set is also summarized (right).

5.1 Single-Object Dense Descriptors

We observe that with our training procedures described in Section 3.2, for a wide variety of objects we can acquire dense descriptors that are consistent across viewpoints and configurations. The variety of objects includes moderately deformable objects such as soft plush toys, shoes, mugs, and hats, and can include very low-texture objects (Figure 2). Many of these objects were just grabbed from around the lab (including the authors’ and labmates’ shoes and hats), and dense visual models can be reliably trained with the same net-
We also find that for some low-texture objects, orientation randomization and background domain random-
ization are critical for attaining consistent object descriptors. Otherwise the model may learn to memorize
and encourage consistency (Figure 5b); it is less critical for high-texture objects and larger datasets.

An early observation during experimentation was that overlap in descriptor space naturally occurs if the
same model is trained simultaneously on different singulated objects, where sampling of matches and non-

Figure 3: (a) table describing the different types of networks referenced in experiments. Column labels correspond to
techniques described in Section 3. (a) Plots the cdf of the L2 pixel distance (normalized by image diagonal, 800 for
a 640 x 480 image) between the best match \(u_b\) and the true match \(u^*_b\), e.g. for standard-SO in 93% of image pairs
the normalized pixel distance between \(u^*_b\) and \(u_b\) is less than 13%. All networks were trained on the same dataset
using the labeled training procedure from (a). (c) Plots the cdf of the fraction of pixels \(u_b\) of the object pixels with
\(D(I_a,u^*_b,I_b,u_b) < D(I_a,u^*_b,I_b,u_b^*)\), i.e. they are closer in descriptor space to \(u^*_b\) than the true match \(u_b^*\).

Figure 4: Comparison of training without any distinct object loss (a) vs. using cross-object loss (b). In (b), 50% of
training iterations applied cross-object loss and 50% applied single-object within-scene loss. The plots show a scatter of the descriptors for 10,000 randomly-selected pixels for
each of three distinct objects. Networks were trained with \(D = 2\) to allow direct cluster visualization. (c) Same axes as
Figure 3 (a). All networks were trained on the same 3 object dataset. Networks with a number label were trained with
cross object loss and the number denotes the descriptor dimension. no-cross-object is a network trained without cross
object loss.

work architecture and training parameters. The techniques in Section 3.2 provide significant improvement
in both (a) qualitative consistency over a wide variety of viewpoints, and (b) quantitative precision in cor-
respondences. As with other works that learn pairwise mappings to some descriptor space [30], in practice
performance can widely vary based on specific sampling of data associations and non-associations used dur-
ing training. One way to quantitatively evaluate correspondence precision is with human-labeled (used only
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matches was only performed within scene. Since there is no component of the loss function that requires different objects to occupy different subsets of descriptor space, the model maps them to an overlapping subset of descriptor space, distinct from the background but not each other (Figure 4a). Accordingly we sought to answer the question of whether or not we could separate these objects into unique parts of descriptor space.

By applying cross-object loss (Section 3.3.i, training mode specific in Figure 3a), we can convincingly separate multiple objects such that they each occupy distinct subsets of descriptor space (Figure 4). Note that cross-object loss is an extension of sampling across scene as opposed to only within scene. Given that we can separate objects in descriptor space, we next investigate: does the introduction of object distinctness significantly limit the ability of the models to achieve correspondence precision for each individual object? For multi-object datasets, we observe that there is a measurable decrease in correspondence precision for small-dimensional descriptor spaces when the cross-object loss is introduced, but we can recover correspondence precision by training slightly larger-dimensional descriptor spaces (Figure 4c). For the most part, 3-dimensional descriptor spaces were sufficient to achieve saturated (did not improve with higher-dimension) correspondence precision for single objects, yet this is often not the case for distinct multi-object networks.

5.3 Selective Class Generalization or Instance Specificity

Surprisingly we find that when trained simultaneously on similar items of a class using training mode consistent, the learned descriptors naturally generalize well across sufficiently similar instances of the class. This result of converging descriptors across a class is similar to the surprising generalization observed for human datasets in [7, 8]. Here we show that we can obtain class consistent dense descriptors for 3 different classes of objects (hats, shoes, and mugs) trained with only static-scene data association. We observe that the descriptors are consistent despite considerable differences in color, texture, deformation, and even to some extent underlying shape. The training requirements are reasonably modest – only 6 instances of hats were used for training yet the descriptors generalize well to unseen hats, including a blue hat, a color never observed during training. The generalization extends to instances that a priori we thought would be failure modes: we expected the boot (Figure 6h) to be a failure mode but there is still reasonable consistency with other shoes. Sufficiently different objects are not well generalized, however – for example Baymax and Starbot (Figure 2e,f) are both anthropomorphic toys but we do not attain general descriptors for them. While initially we proposed research into further encouraging consistency within classes, for example by training a Dense Object Net to fool an instance-discriminator, the level of consistency that naturally emerges is remarkable and was sufficient for our desired levels of precision and applications.

For other applications, however, instance-specificity is desired. For example, what if you would like your robot to recognize a certain point on hat A as distinct from the comparable point on hat B? Although we could separate very distinct objects in multi-object settings as discussed in the previous section, it wasn’t obvious to us if we could satisfactorily separate objects of the same class. We observe, however, that by applying the multi-object techniques (specific in Figure 3) previously discussed, we can indeed learn distinct descriptors even for very similar objects in a class (Figure 6iv).

5.4 Example Applications to Robotic Manipulation: Grasping Specific Points

Here we demonstrate a variety of manipulation applications in grasping specific points on objects, where the point of interest is specified in a reference image. We emphasize there could be many other applications, as mentioned in the Conclusion. In our demonstrations, a user clicks on just one pixel \( u^*_a \) in one reference
image. Now the robot has the ability to autonomously identify the corresponding point in new scenes via Equation 6. Akin to other works with similarity learning in metric spaces [30], we set a simple threshold to determine whether a valid match exists. If a match is identified in the new scene we can instruct the robot to autonomously grasp this point by looking up the corresponding location in the point cloud and using simple geometric grasping techniques (details in Appendix C).

The particular novel components of these manipulation demonstrations are in grasping the visual corresponding points for arbitrary pixels that are either in different (potentially deformed) configurations (Fig. 6i-ii), general across instances of classes (Fig. 6iii), or instance-specific in clutter (Fig. 6iv). Our video best displays these tasks. Note that only a dense (as opposed to sparse) method can easily accommodate the arbitrary selection of interaction points, and class-generalization is out of scope for hand-designed descriptors such as SIFT. This is also out of scope for general grasp planners like [3, 18, 2, 20] which lack any visual object representation, and for segmentation based methods [18, 5, 4] since the visual representation provided by segmentation doesn’t capture any information beyond the object mask.

This work introduces Dense Object Nets as visual object representations which are useful for robotic manipulation and can be acquired with only robot self-supervision. Building on prior work on learning pixel-level data associations we develop new techniques for object-centricness, multi-object distinct descriptors, and learning dense descriptors by and for robotic manipulation. Without these object-centric techniques we found that data associations from static-scene reconstructions were not sufficient to achieve consistent object descriptors. Our approach has enabled automated and reliable descriptor learning at scale for a wide variety of objects (47 objects, and 3 classes). We also show how learned dense descriptors can be extended to the multi object setting. With new contrastive techniques we are able to train Dense Object Nets that map different objects to different parts of descriptor space. Quantitative experiments show we can train these multi object networks while still retaining the performance of networks that do not distinguish objects. We also can learn class-general descriptors which generalize across different object instances, and demonstrated this result for three classes: shoes, hats, and mugs. Using class-general descriptors we demonstrate a robot transferring grasps across different instances of a class. Finally we demonstrate that our distinct-object techniques work even for objects which belong to the same class. This is demonstrated by the robot grasping a specific point on a target shoe in a cluttered pile of shoes. We believe Dense Object Nets can enable many new approaches to robotic manipulation, and are a novel object representation that addresses goals (i-iv) stated in the abstract. In future work we are interested to explore new approaches to solving manipulation problems that exploit the dense visual information that learned dense descriptors provide, and how these dense descriptors can benefit other types of robot learning, e.g. learning how to grasp, manipulate and place a set of objects of interest.

6 Conclusion

This work introduces Dense Object Nets as visual object representations which are useful for robotic manipulation and can be acquired with only robot self-supervision. Building on prior work on learning pixel-level data associations we develop new techniques for object-centricness, multi-object distinct descriptors, and learning dense descriptors by and for robotic manipulation. Without these object-centric techniques we found that data associations from static-scene reconstructions were not sufficient to achieve consistent object descriptors. Our approach has enabled automated and reliable descriptor learning at scale for a wide variety of objects (47 objects, and 3 classes). We also show how learned dense descriptors can be extended to the multi object setting. With new contrastive techniques we are able to train Dense Object Nets that map different objects to different parts of descriptor space. Quantitative experiments show we can train these multi object networks while still retaining the performance of networks that do not distinguish objects. We also can learn class-general descriptors which generalize across different object instances, and demonstrated this result for three classes: shoes, hats, and mugs. Using class-general descriptors we demonstrate a robot transferring grasps across different instances of a class. Finally we demonstrate that our distinct-object techniques work even for objects which belong to the same class. This is demonstrated by the robot grasping a specific point on a target shoe in a cluttered pile of shoes. We believe Dense Object Nets can enable many new approaches to robotic manipulation, and are a novel object representation that addresses goals (i-iv) stated in the abstract. In future work we are interested to explore new approaches to solving manipulation problems that exploit the dense visual information that learned dense descriptors provide, and how these dense descriptors can benefit other types of robot learning, e.g. learning how to grasp, manipulate and place a set of objects of interest.

See video (https://youtu.be/L5UW1VapKNE) for extensive videos of the different types of robot picking.
Acknowledgments

The authors thank Duy-Nguyen Ta, Alex Alspach, and Yunzhi Li for help with calibration, hardware, and training techniques. We also thank Tanner Schmidt for helpful comments in preparing the paper. This work was supported by: Army Research Office, Sponsor Award No. W911NF-15-1-0166; Draper Laboratory Incorporated, Sponsor Award No. SC001-000001002; Lincoln Laboratory/Air Force, Sponsor Award No. 7000374874; Amazon Research Award, 2D-01029900; Lockheed Martin Corporation, Sponsor Award No. RPP2016-002. Views expressed in the paper are not endorsed by the sponsors.

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Appendix A  Experimental Hardware

All of our data was collected using an RGBD camera mounted on the end effector of a 7 DOF robot arm (see Figure 7). We used a Kuka IIWA LBR robot with a Schunk WSG 50 parallel jaw gripper. A Primesense Carmine 1.09 RGBD sensor was mounted to the Schunk gripper and precisely calibrated for both intrinsics and extrinsics.

Appendix B  Experimental Setup: Data Collection and Pre-Processing

As discussed in the paper all of our data consists of 3D dense reconstructions of a static scene. To collect data for a single scene we place an object (or set of objects) on a table in front of the robot. We then perform a scanning pattern with the robot which allows the camera to capture many different viewpoints of the static scene. This procedure takes about 70 seconds during which approximately 2100 RGBD frames are captured (the sensor outputs at 30Hz). Using the forward kinematics of the robot, together with our camera extrinsic calibration, we also record the precise camera pose corresponding to each image. Since we have the camera poses corresponding to each depth image we use TSDF fusion [27] to obtain a dense 3D reconstruction. Although we use our robot’s forward kinematics to produce the dense 3D reconstruction together with camera pose tracking, any dense SLAM method (such as [28]) could be used instead. In practice we found that using the robot’s forward kinematics to obtain camera pose estimates produces very reliable 3D reconstructions which are robust to lack of geometric or rgb texture, varying lighting conditions, etc. Next we obtain new depth images for each recorded camera frame by rendering against the 3D reconstruction using our camera pose estimates. This step produces depth images which are globally consistent and free of artifacts (i.e. missing depth values, noise etc.). This keeps the process of finding correspondences across RGB images as a simple operation between poses and depth images. To enable the specific training techniques discussed in the paper we also need to know which parts of the scene correspond to the objects of interest. To do this we implemented the change detection technique of [24]. In practice since all of our data was collected on a tabletop, and our reconstructions can be easily globally aligned (due to the fact that we know the global camera poses from the robots forward kinematics) we can simply crop the reconstruction to the area above the table. Once we have isolated the part of the reconstruction corresponding to the objects of interest, we can easily render binary masks via the same procedure as was used to generate the depth images.

Our RGBD sensor captures images at 30Hz, so we downsample the images to avoid having images which are too visually similar. Specifically we downsample images so that the camera poses are sufficiently different (at least 5cm of translation, or 10 degrees of rotation). After downsampling we are left with approximately approximately 315 images per scene.

In between collecting RGBD videos, the object of interest should be moved to a variety of configurations, and the lighting can be changed if desired. While for many of our data collections a human moved the object between configurations, we have also implemented and demonstrated (see our video) the robot autonomously rearranging the objects, which highly automates the object learning process. We employ a Schunk two-finger gripper and plan grasps directly on the object point cloud (see Appendix C). If multiple different objects are used, currently the human must still switch the objects for the robot and indicate which
scenes correspond to which object, but even this information could be automated by the robot picking objects from an auxiliary bin and use continuity to simply identify which logs are of the same object.

Appendix C  Grasping Pipeline

All of the grasping demonstrated in the paper uses simple geometric point cloud based techniques. When the robot wants to grasp something it moves to a few pre-specified poses and records a depth image. These depth images are then fused into a pointcloud using the camera poses estimated from forward kinematics. There are two types of grasping that are performed in the paper. The first is grasping the object to automatically reorient it during data collection. To achieve this we first randomly sample many grasps and prune those that are in collision. The remaining collision free grasps are then scored by a simple geometric criterion that evaluates the grasps for antipodality. The highest scoring grasp is then chosen for execution. If, as in Section 5.4 of the paper, we are attempting to grasp a specific point, then the procedure is almost the same, with the slight modification that all the randomly sampled grasps are centered around the target grasp point. Although there are a variety of learning based grasping algorithms [3, 2] that could have been used, we found that our simple geometric based grasp planning was sufficient for the tasks at hand.

Appendix D  Network Architecture and Training Details

For our network we use 34-layer, stride-8 ResNet (pretrained on ImageNet), and then bilinearly upsample to produce a full resolution $640 \times 480$ image.

For training, at each iteration we randomly sample between some specified subset of specified image comparison types (Single Object Within Scene, Different Object Across Scene, Multi Object Within Scene, Synthetic Multi Object). The weighting between how often each type is chosen is done via specifying their probabilities of being selected. Once the type has been sampled we then sample some set of matches and non-matches for each (around 1 million in total). Each step of the optimizer uses a single pair of images.

All the networks were trained with the same optimizer settings. Networks were trained for 3500 steps using an Adam optimizer with a weight decay of $1e^{-4}$. Training was performed on a single Nvidia 1080 Ti or Titan Xp, a single step takes approximately 0.22 seconds, i.e. approximately 13 minutes, and so together with collecting a handful of scenes the entire training for a new object can take 20 minutes. The learning rate was set to $1e^{-4}$ and dropped by 0.9 every 250 iterations. The networks trained with procedure specific used a 50-50 split of within scene image pairs and across scene image pairs 50% of the time. For the network used to grasp the heel of the red/brown shoe in Section 5.4 we sampled equally the three data types (Single Object Within Scene, Different Object Across Scene, Synthetic Multi Object).