

# Bayesian Optimization of 3D Feature Parameters for 6D Pose Estimation

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**Abstract:** 6D pose estimation using local features has shown state-of-the-art performance for object recognition and pose estimation from 3D data in a number of benchmarks. However, this method requires extensive knowledge and elaborate parameter tuning to obtain optimal performances. In this paper, we propose an optimization method able to determine feature parameters automatically, providing improved point matches to a robust pose estimation algorithm. Using labeled data, our method measures the performance of the current parameter setting using a scoring function based on both true and false positive detections. Combined with a Bayesian optimization strategy, we achieve automatic tuning using few labeled examples. Experiments were performed on two recent RGB-D benchmark datasets. The results show significant improvements by tuning an existing algorithm, with state-of-art performance.

## 1 INTRODUCTION

Pose estimation is the task of determining the position and orientation of one or multiple objects in a scene, e.g. as seen in Fig. 1. The scene data could be either 2D or 3D data coming from one or multiple sensors. A wide range of new sensors, with the Kinect (Zhang, 2012) at the forefront, has enabled easy access to 3D data. This has resulted in 3D feature matching as a viable tool for pose estimation. The pose is represented by a transformation matrix consisting of a translation and rotation, which can be passed on for further use, e.g. during robotic grasping.

A widely used method for addressing the task of pose estimation in 3D data is feature matching using local shape descriptors. This method goes back 20 years with the well-known Spin Images (Johnson and Hebert, 1999) and has become the de facto standard for 3D pose estimation (Guo et al., 2014). Matches between object and scene points are found in feature space and are used to find the transform between the to point clouds. This approach is especially suitable for scenarios where parts of the object are occluded, as the matching is performed locally. Many different features have been developed, e.g. SHOT (Salti et al., 2014), FPFH (Rusu et al., 2009), and USC (Tombari et al., 2010). A fundamental limitation when applying such descriptors is that the performance depends heavily on careful parameter tuning, the size of the lo-



Figure 1: Multi-instance pose estimation example for a scene from the dataset of (Tejani et al., 2014). To the top is shown an example with non-optimized feature parameters, resulting in two correct (green) and one incorrect detection (red). The CAD model of the object is shown in the middle. Our parameter optimization improves the pose estimation algorithm, giving correct detection of all the three instances of the object shown at the bottom.

cal support radius is shown to be extremely important (Guo et al., 2016), which must be set to a compromise between descriptive power and occlusion tolerance. If set incorrectly, the matching will perform badly

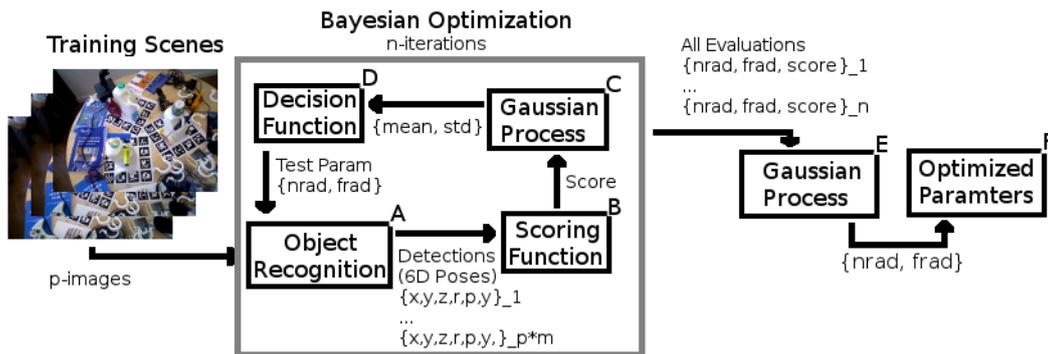


Figure 2: Full pipeline of our parameter optimization approach. ‘p’ training scenes are selected and for each scene ‘m’ objects are present. Resulting in  $m \times p$  object detections. **A**: First a parameter set is used for object recognition. **B**: The scoring function then determines the performance. **C**: The Gaussian Process fits a distribution to the results. **D**: The decision selects the next parameters sets to test. A number of preselected parameter sets are used to build the Gaussian Process, after which the Bayesian Optimization runs for  $n$ -iterations. **E**: the full set of parameters and scores is fit to an additional Gaussian Process and the expected best parameter set is found **F**.

and so will the pose estimation algorithm, which uses these matches for the sampling process.

In a comparison of different features, this variability is shown as an error greatly influencing performance (Guo et al., 2016). And in papers presenting the performance of new features the tuning is done by the author who searches for the best performance, and leaves out all other results. We believe the parameter values to be fundamental in the feature matching task and propose a systematic approach to choosing the best parameters.

Although the data-driven approach for object recognition for 3D data is old (Oshima and Shirai, 1983), the knowledge-driven fine tuning is the one often seen in benchmarking. In this paper we focus on the data-driven approach. Scenes are split into a training and test set, but compared to modern approaches towards 3D tasks, e.g. (Qi et al., 2017), we also show good results with much smaller training samples. Additionally, we employ Bayesian Optimization (Snoek et al., 2012) to search the parameter space. But as we are only searching a small dataset, instead of using a single maximum value we fit a Gaussian process (Rasmussen, 2004) to the results to avoid local maximums. An overview of the full method can be seen in Fig. 2.

In a study of the usage of pose estimation, the median time to setup a system was found to be between 1–2 weeks (Hagelskjær et al., 2017), with most of the work being done on the software side. To enable an easier use of object recognition in real applications, automatic optimization approaches can be helpful. This paper presents a principled method for doing so, with a focus on some of the most important parameters for local shape descriptor computation. Our method, however, can be applied in a wide range of

applications.

The remaining article is structured as follows: Section 2 outlines the methods used for pose estimation along with other optimization approaches. Our method is presented in Section 3. Section 4 contains experimental results of our method compared with current methods. Finally, we outline the conclusion of our work and the further perspectives of this approach.

## 2 PROPOSED METHOD

Parameter tuning using Bayesian Optimization has begun to be widely used in machine learning. Despite this, to the best of our knowledge, automatic parameter tuning has not yet been seen for 3D feature descriptors. Although e.g. (Jørgensen et al., 2018) cover optimal camera placements in a robotic setup, it does not go into the parameters of feature matching. We start by outlining the feature matching for pose estimation task, then we outline the Bayesian Optimization method and finally we describe how it is used to tune parameters.

### 2.1 Pose Estimation with Feature Matching

Pose estimation based object recognition is the task of determining the position of one or multiple objects in a scene. A typical strategy towards a solution to this problem is to represent the scene by a 2D image, wherein template matching of object views are performed (Hinterstoisser et al., 2012). This approach, however, is not well suited to handle occlusi-

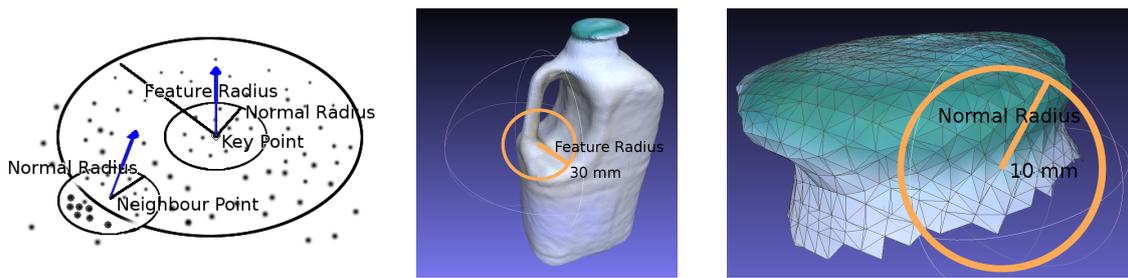


Figure 3: The important descriptor parameters for a single point in a point cloud. To the left is shown a representation of parameters: For each point, the Normal Radius is used to select nearby points for calculating the normal vector. All points within the Keypoint Radius is then used to compute the descriptor. In the middle the size of feature radius is shown, the 30 mm represent 10 % of the object size. To the right is shown a 10 mm normal radius, zoomed.

ons of the object. Feature based methods such as e.g. SIFT (Lowe, 1999) were developed, which describe local patches. At roughly the same time, new descriptors were also developed for 3D data, e.g. the Spin Image descriptor (Johnson and Hebert, 1999). The Spin image is a local descriptor based on the idea of an object-centered viewpoint. In the 2D case the local descriptor is calculated with orientation towards the camera, as the geometry is unknown. In the 3D case the normal vector at the point can be calculated and instead of using the coordinate system of the camera, a local coordinate system is found. This makes the descriptor much more robust to both translation and rotation in depth (Hagelskjaer et al., 2017). The object-centered viewpoint is used for many of the following descriptors which have later been developed. The Spin Image encodes the number of points that fall into nearby spatial bins, relative to the surface point being described. This use of relational information has been used in many following descriptors, for instance SHOT (Salti et al., 2014), FPFH (Rusu et al., 2009), and USC (Tombari et al., 2010), to name a few. In this work we use local shape descriptor which collects four simple relations for each point in the spherical neighborhood around the point to be described. These relations are taken from the point pair feature (PPF) (Drost et al., 2010) and rely on the computation of surface normals, similar to the majority of other shape descriptors available. The relations are binned into a number of histograms, which together describe the local shape variation. This descriptor has been successfully used earlier for pose estimation and object recognition tasks (Buch et al., 2017). An illustration of the computation of the PPF based feature in a scene with corresponding parameters is shown in Fig. 3. Using training-data for pose estimation have also been performed using deep learning (Kehl et al., 2017; Rad and Lepetit, 2017; Do et al., 2018). These approaches show impressive performance, but have a number of limitations. The trained network is a complex model with many parameters requiring a large

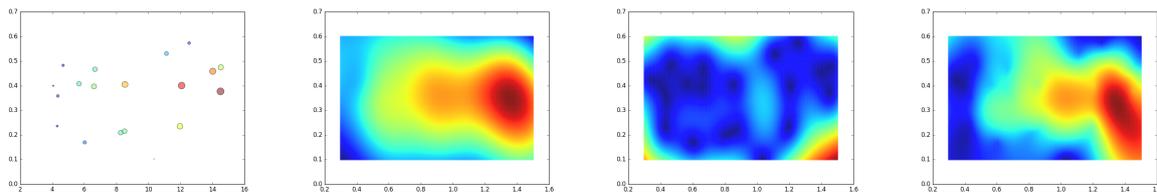
amount of well representing data. This restricts the setup of new systems as training data needs to either collected or generated. These methods expects the object standing on a table and have not been tested on the bin-picking dataset. Compared to this our approach is based on methods only requiring a CAD model.

## 2.2 Optimization Strategy

In the previous section the importance of choosing correct values for shape descriptor parameters were highlighted. It is, therefore, necessary to explore the parameter space and obtain an optimum configuration according to some criterion. An exhaustive search of the full parameter space is intractable, thus it is desirable to derive a proper search strategy.

### 2.2.1 Optimization Algorithms

Optimization algorithms in general is a widely studied subject, and a number of different methods exist. One of the more straightforward approaches is gradient descent wherein the gradient of the loss function is used to update the parameter setting. Thus, given a starting point, the parameters are gradually updated until a maximum is found. This also has the advantage that it can be easily specified when to terminate the optimization. For the pose estimation problem two difficulties for gradient descent arise. First, the loss function cannot be expected to be either smooth or convex. Fundamentally, the score is the number of correct detections, which is a subset of the list of natural numbers  $\mathbb{N}$ . The gradient of this function cannot be expected to be non zero. As a limited number of scenes are used for our purposes, the score function will be expected to fluctuate. It is, therefore, necessary to perform non-smooth non-convex optimization, for which many different methods have been developed (Rios and Sahinidis, 2013).



(a) Score for different parameters set run on the training data. (b) The resulting mean of the fitted Gaussian Process. (c) The resulting variance of the fitted Gaussian Process. (d) The Upper Confidence Bound plot by combining mean and variance.

Figure 4: Loop of a single Bayesian optimization. Notice the variance is zero at each data point. The next iteration will be at the highest point in the Upper Confidence Bound plot.

### 2.2.2 Bayesian Optimization

We decided to use Bayesian optimization, a method for bounded global optimization (Snoek et al., 2012). Bayesian optimization has been employed successfully for tuning machine learning parameters as well as many other applications (Bergstra et al., 2013), and an implementation is readily available (Snoek et al., 2012). Bayesian optimization is also a good approach when evaluations are expensive as is the case of pose estimation. Benchmarking of optimization algorithms have shown Bayesian Optimization with state-of-art performance (Jones, 2001). Compared with other non-gradient methods, i.e. evolutionary algorithms and particle filters Bayesian Optimization use qualified guesses and not random mutations and sampling and thus requires fewer iterations.

In Bayesian optimization all previous samples are used to fit a surrogate model and using this surrogate model the next sample to evaluate is selected. A number of initial samples are made using random uniform sampling within the bounds for the parameters. The used surrogate model is a Gaussian process (Rasmussen, 2004), a non-parametric method which utilizes all previous samples to create the model. Additionally, the Gaussian process also provides a probability of the prediction. The well-known Upper Confidence Bound (UCB) is used as the acquisition function (Snoek et al., 2012). As the name implies the confidence bound over the current maximum is used to select the next parameter setting to investigate. An illustration of the a single step in the Bayesian optimization can be seen in Fig. 4.

## 2.3 Our Approach

The pose estimation system we optimize is based on the voting approach presented in (Buch et al., 2017). This algorithm is freely available online<sup>1</sup> and direct comparison can be performed with existing results.

<sup>1</sup><https://www.gitlab.com/caro-sdu/covis>

We decide to optimize the size of the feature radius and the normal radius, as these parameters are fundamental to all feature matching algorithms and are easily understood. The goal of our approach is to find the parameter set which gives the best performance for pose estimation. For the datasets used in this work, recall and maximum F1-score were used (Hinterstoisser et al., 2012; Tejani et al., 2014) to evaluate performance of a recognition system. Recall is defined as the number of correct detections found from the full dataset. A detection is defined as correct if the translation distance is less than 50 mm and the angular error for the Z-axis is less than 15°. F1-score is defined as a combination of both recall and precision, where precision is the number of correct detections to the number of returned detections.

### 2.3.1 Scoring the Detections

To optimize for stable detections, we utilize the score given from the detection algorithm to create a new score for the optimization system. We split the scores given by the system into correct (true positives, TPs) and wrong detections (false positives, FPs), thus getting respectively  $KDE_{TP}$  and  $KDE_{FP}$ . The  $KDE$  is the output kernel density score for a pose provided by the underlying pose voting method (Buch et al., 2017) used for the estimation, but any scoring function could in principle be used here. We then use the TP/FP ratio as the score, as seen in (1), penalizing has high scores for wrong detections and rewarding high scores for correct detections. The score function is log-transformed for numerical reasons, as this leads to more stable performance when invoking the optimization algorithm.

$$\begin{aligned} score(KDE) &= \begin{cases} \log\left(\frac{\sum KDE_{TP}}{\sum KDE_{FP}}\right), & \text{if } \sum KDE_{TP} \geq \sum KDE_{FP} \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (1)$$

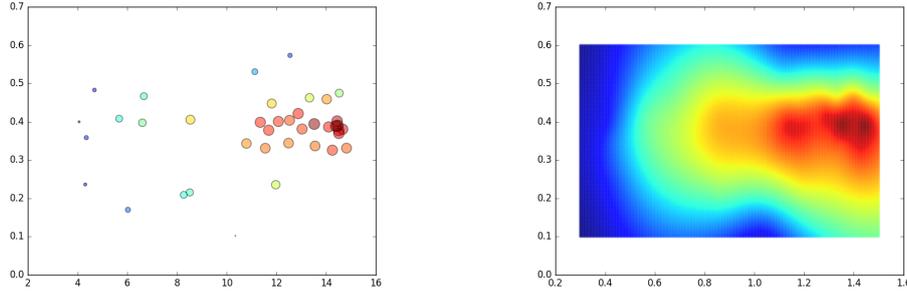


Figure 5: Result of fitting a Gaussian process to the samples from the Bayesian optimization. The best parameter set is then found by the maximum position of the resulting fit.

### 2.3.2 Gaussian Process Regression for Mode Finding

As only a small training set is used, there is a risk of overfitting the parameters to only the particular set of training scenes seen during training. To decrease the risk of wrong parameters we additionally employ a Gaussian Process to regress over the finished set of evaluations, which is then used to predict the best parameter set in a more smooth and robust manner.

Other approaches have also been made to avoid overfitting Bayesian optimization techniques to sparse training sets. In (Dai Nguyen et al., 2017) a term is added to the acquisition function which penalizes sharp peaks. In our approach we focus on exploration, but use the classical Bayesian optimization, and then fit all explored points with a Gaussian Process to determine a stable maximum. The number of explored points,  $n$ , can be described as the matrix consisting of the parameters  $X$  and the resulting score  $y$ .

$$X, y = \{(x_i, f(x_i)) \mid i = 1, \dots, n\} \quad (2)$$

To predict the expected score at new parameter values with a Gaussian Process, a distribution is required. Here  $\hat{x}$  is denoting a new untested parameter set.

$$\begin{bmatrix} y \\ \hat{x} \end{bmatrix} \sim \begin{bmatrix} K & K_{\hat{x}}^T \\ K_{\hat{x}} & K_{\hat{x}\hat{x}} \end{bmatrix} \quad (3)$$

Where  $K$  is a covariance matrix given by a selected kernel,  $k(x_1, x_2)$ , wherein each index is calculated by the relationship of two parameter sets. This gives that  $K_{n \times n}$ ,  $K_{n \times 1}$  and  $K_{\hat{x}\hat{x}}$ . We are now able to find the expected value of the new parameter set by the mean and the uncertainty as the variance (Ebden, 2008).

$$E(\hat{x}) = K_{\hat{x}} K^{-1} y \quad (4)$$

$$\text{var}(\hat{x}) = K_{\hat{x}\hat{x}} - K_{\hat{x}} K^{-1} K_{\hat{x}}^T \quad (5)$$

To make the Gaussian process more stable to noise, a second term is added to the covariance

function, compared with the Bayesian Optimization (Snoek et al., 2012), giving a Matern-kernel and a White Noise kernel, as shown in (6). Here the kernel function  $K$  takes distance  $d$  as input, combining the Matern covariance  $C_v$  and a diagonal noise term  $N$ .

$$K(d) = C_v(d) + N(d) \quad (6)$$

$\Gamma$  and  $J$  denote the gamma function and the Bessel function, respectively. The white noise (8) adds the uncertainties in the evaluation as the full dataset is not used. An illustration of a 2D regression can be seen in Fig. 5, representing the scores for parameter sets trained the training images shown in Fig. 6.

$$C_v(d) = \sigma^2 + \frac{2^{1-\nu}}{\Gamma(\nu)} \left( \sqrt{2\nu} \frac{d}{\rho} \right)^\nu J_\nu \left( \sqrt{2\nu} \frac{d}{\rho} \right) \quad (7)$$

$$N(d) = \begin{cases} \sigma, & \text{if } d = 0 \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

This kernel is used to create the covariance matrices, but before the prediction can be calculated, parameters for (7) and (8) need to be determined. A minimization using (Byrd et al., 1995) is performed that fits the parameter values to the known score  $y$  while fixing the  $\nu$  value, i.e. how much distant points interact with predicted result. This is to ensure a more smooth prediction of parameters. With these values the kernel can be calculated and a more robust function for the expected parameter space can be created.

Using the training data and the scoring system the parameter space is explored using Bayesian optimization and a number of samples are collected. These samples are then used to fit a Gaussian process as seen in (6) from which a maximum parameter set is found.

Table 1: Results for the tabletop dataset (Tejani et al., 2014). All results are given as F1 scores.

Method	Camera	Coffee	Joystick	Juice	Milk	Shampoo	Avg
(Doumanoglou et al., 2016)	<b>0.903</b>	0.932	0.924	0.819	0.510	0.735	0.803
(Kehl et al., 2017)	0.603	0.991	0.937	<b>0.977</b>	<b>0.954</b>	0.859	0.856
(Li and Hashimoto, 2018)	0.741	0.983	<b>0.997</b>	0.919	0.780	<b>0.999</b>	0.910
Org (Buch et al., 2017)	0.711	0.993	0.973	0.975	0.776	0.709	0.856
Ours	0.853	<b>0.999</b>	0.994	0.973	0.859	0.796	<b>0.912</b>

### 3 EXPERIMENTS

We ran extensive evaluations on two commonly used RGB-D based object recognition datasets. The first dataset of Tejani et al. (Tejani et al., 2014) contains six tabletop sequences for multi-instance pose estimation (see Fig. 1 for an example). The scenes contain large amounts of cluttering and background structures. The second dataset of Doumanoglou et al. (Doumanoglou et al., 2016) contains two objects (a coffee cup and a juice box) and three test sequences, all showing multiple instances of the objects in a bin. There is a dedicated sequence per object and a mixed sequence, where both objects appear in the bin.

#### 3.1 Selection of Training Images

The tested datasets unfortunately do not have training scenes, which required us to take some out for training. In (Brachmann et al., 2016) a scheme for selecting training data in already existing datasets have been proposed. This scheme has been reused in a number of papers (Rad and Lepetit, 2017; Tekin et al., 2018). This approach samples the full range of poses in the dataset by adding all images that deviate more than 15 degrees from images already in the training set. An example of the difference between each training image is shown in Fig. 6. As this would cover 33 percent of the dataset for the bin picking dataset a different approach is chosen in this article.

From each dataset, we collected eight random scenes for training, considerable less than the more than 100 used in (Brachmann et al., 2016; Rad and Lepetit, 2017; Tekin et al., 2018).

For our optimization, ten initial parameter samples drawn uniformly in space and 25 subsequent iterations were made using Bayesian optimization with our KDE scoring. Lastly the Gaussian process regression model was fitted and a maximum was calculated. A specific example can be seen in Fig. 1, where our method enable successful recognition of all three instances of a model in a scene from the tabletop dataset.

#### 3.2 Results

Comparison was done with the original pose voting method (Buch et al., 2017) and for the tabletop dataset we included the current state of the art (Doumanoglou et al., 2016; Li and Hashimoto, 2018) from the literature. Compared with the original pose voting algorithm, we obtain a 7% increase in performance on the tabletop scenes on average (second column from the right). Interestingly, our optimization also allows the pose voting method to surpass state of the art on this dataset. For completeness, we have additionally included a rightmost column where we do not include the eight training scenes in the testing to show that this causes a marginal difference in results.

For the bin picking dataset (Doumanoglou et al., 2016) no current method seems to outperform (Buch et al., 2017), we decided to include two other known methods to show not only compare with the original approach. The results can be seen in Tab. 2. Here we substantially outperform the baseline on average, but perform slightly worse on the coffee cup. We believe this is because the performance on this object close to saturated already, with the chosen parameters.

Table 2: Results for bin picking dataset (Doumanoglou et al., 2016). All results are given as recall rates, as per the protocol for this dataset.

Method	Coff	Juice	Avg.
(Tejani et al., 2014)	31.4	24.8	28.1
(Doumanoglou et al., 2016)	36.1	29.0	32.6
Org (Buch et al., 2017)	<b>63.8</b>	44.9	54.4
Ours	63.4	<b>51.7</b>	<b>57.6</b>

#### 3.3 Sensitivity to the Number of Training Images

We also wanted to test the ability of our method to generalize to the test set using a varying number of training scenes. This experiment was performed on the bin picking dataset. It is clear from Fig. 7 that the number of scenes is important for the resulting performance. As the number of scenes increases, so does the performance in general, although eight scenes in



Figure 6: Sequence of the first four images used for the training of object "05" of the Tejani dataset. There is atleast a 15 degree angle between each object.

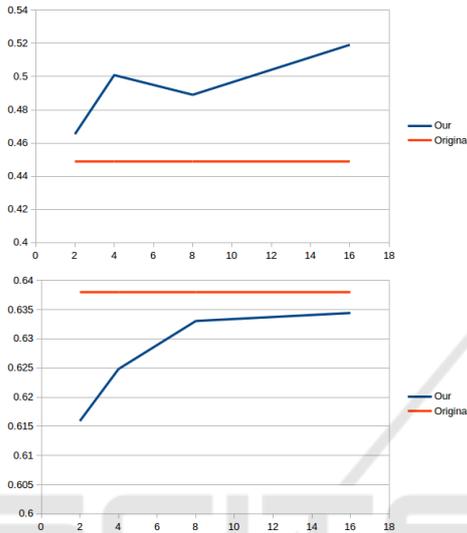


Figure 7: Results of fitting a Gaussian process to increasing training set sizes from the bin picking dataset. To the left is shown the result of varying the number of training scenes for the juice, and to the right the same for the coffee cup.

the juice dataset gives a drop. This is likely from an unfortunate random sample of a subset of scenes that do not properly represent the full data. For the coffee cup dataset the performance is slightly increasing as more samples are added, although it is still not able to outperform the original. A 1 dimensional grid search was performed on the full dataset which shows that the original performance is actually at the best possible and all our found parameter sets are circling around this performance.

## 4 CONCLUSIONS

In this work we have demonstrated the feasibility of using Bayesian optimization in combination with Gaussian Process regression for automatically determining optimal parameters for an existing 3D shape descriptor based object recognition and pose estimation system. Our method is useful for bounded global optimization within a chosen parameter space that is crucial to the performance of the method that is to

be tuned. We have demonstrated our approach on a recent pose estimation algorithm, optimizing two of the most important hyper-parameters for the descriptor calculation process.

Our method is able to significantly improve the performance on the chosen pose estimation algorithm, providing improved results compared to state the art algorithms on two RGB-D datasets. We see our method as more generally applicable for optimization of many other parameters than the two descriptor parameters used in this work. We will pursue this direction for future work.

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