

Multi-Armed Bandit Models for Sample-Based Grasp Planning in the Presence of Uncertainty [v-13 09-30-2014]

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Abstract—Gaussian Process Implicit Surface (GPIS) have emerged recently as a new probabilistic shape representation. Former methods for grasp evaluation with shape uncertainty require sampling from distributions on shape. Given a GPIS model this would mean sampling from the signed distance field in a uniform grid of side length n . The computational complexity of this operation is $O(n^6)$ in 2D and $O(n^9)$ in 3D. We propose an alternative to sampling from shape distributions and demonstrate how this reduces the computational complexity to $O(n^3)$ in both 3D and 2D for evaluation of a single grasp. We furthermore introduce the idea of adaptive sampling in the context of choosing the best grasp given a set of grasps and a GPIS object model by formulating it as a budgeted multi-arm bandit problem. We show an order of magnitude reduction in the number of samples needed vs. a non-adaptive approach and we have statistical guarantees with our method.

I. INTRODUCTION

[TODO: GET HIGH RES GPIS VISUALIZATIONS, INCORPORATE NEXT ROUND OF FEEDBACK] Consider a robot packing boxes in a shipping warehouse environment. The robot will frequently encounter objects that it has not seen before. The robot will have to plan stable grasps without any prior information other than its sensor data. As seen in Fig. 1, with today’s RGB and depth sensors, surface properties, such as specularity and transparency, can greatly effect the returned observations. Grasp planners based on deterministic algorithms are not designed to handle such noise and could fail. To plan grasps in a partially observed world, recent research has focused on incorporating uncertainty in the shape of the object [1], [2], [3].

While past work has encoded uncertainty in a polygonal mesh representation [1], an alternative is to work with the signed distance fields (SDFs), a continuous valued function that is an implicit surface: zero-valued at the surface of the object, positive value outside the surface and negative valued inside the surface. This representation is growing in popularity in the robotics field for its ability to integrate range data in real time [4], [5]. To incorporate uncertainty one can use a Gaussian Process Implicit Surface (GPIS), a Gaussian process over signed distance field. Not only does GPIS present a straightforward and formal way to incorporate measurements from visual, laser and tactile sensors, they also allow for a continuous differentiable function on shape, which can be used for a feedback grasp controller, finding locally optimal grasps and active exploration [6], [?], [7].

Given a method to represent shape uncertainty, a common technique to evaluate grasp quality is to sample from the distribution on shape and perform Monte-Carlo integration on

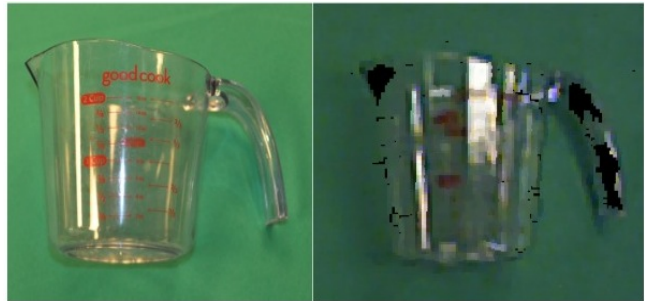


Fig. 1: Left: HD image of a common measuring cup from in a household environment. Right: Image taken from PR2’s Primesense Carmine sensor, large parts of the measuring cup are not detected by the depth sensor and are not visible in the RGB image.

a given grasp metric [1], [8], [2]. Applying this technique to GPIS requires an exhaustive sampling of the signed distance field, which scales $O(n^6)$ for a 2D $n \times n$ workspace and $O(n^9)$ for a 3D workspace. The computational complexity of sampling is derived from the fact sampling from a Gaussian requires matrix inversion of the entire signed distance field. Our paper reduces this complexity to $O(n^3)$ by using the insight that for grasp quality evaluation one only cares about the parameters that define a grasp: contact points, surface normals, center of mass and friction coefficient [9]. We constrain the contact points by considering the approach trajectory of a gripper. Hence, sampling the whole signed distance field is not needed, but instead one can only work with the distributions on grasp parameters given the shape uncertainty model and gripper trajectory. In light of this our contributions are the following:

- 1) Derivation of distributions on grasp parameters given GPIS shape uncertainty model and approach trajectory of gripper.
- 2) Demonstrating both theoretically and empirically how those distributions reduce the computational complexity of sampling.
- 3) Applying adaptive sampling techniques to efficiently find high quality grasps in a given set of proposed grasps.

II. RELATED WORK

Past work on grasping under uncertainty has considered state uncertainty [10], [11], uncertainty in object pose [2], [12], [13], or uncertainty in contact locations with an object [3]. The effect of uncertainty in object geometry on grasp selection has been studied for spline representations of

objects [2], extruded polygonal mesh models [1], [8], and point clouds [14].

Currently, the most common method of evaluating grasp quality under shape and pose uncertainty is to rank a set of random grasps on an object using Monte-Carlo integration on shape and / or pose samples to evaluate a quality measure [2], [1], [8]. Monte-Carlo integration involves drawing random samples from a distribution to approximate an integral [15], which can be slow when the distribution is high-dimensional, such as for distributions on possible shape. To address this, Kehoe et al. [1], [8] demonstrated a procedure for finding a minimum bound on grasp quality given shape uncertainty, which reduced the number of terms needed in Monte-Carlo integration in order to rank grasps, but the method could potentially remove high quality grasps. Laaksonen et al. [16] used Markov Chain Monte Carlo (MCMC) sampling to estimate grasp stability and object pose online under shape and pose uncertainty. MCMC simplified sampling from complicated distributions on pose and shape, but it can be slow to converge to the correct distribution [17].

The multi-armed bandit problem [18], [19], [20] is to maximize the total expected reward over a sequence of possible choices over a set of competing options, each of which has a probabilistic reward function. The optimal sequence of choices if the rewards are known is to always pick the option with the maximum expected reward over the set of possible options. However, to discover which choice is optimal requires a balance between exploration, or choosing options that are not well known, and exploitation, or choosing the current ‘best’ option [18]. Solutions to this problem, called *policies*, include choosing the next option based on Thompson sampling [21], the Gittins index policy [22], and by using an upper confidence bound (UCB) for the expected reward of each option [23]. The UCB can be computed from the sample mean [24], Kullback-Leibler divergence [25], or a prior on the rewards [26]. Solutions to the multi-armed bandit problem are well suited to applications for which it is expensive to exhaustively evaluate all possible options, and therefore these methods have been applied to optimal design of clinical trials [27], market pricing [28], and choosing strategies for games [29].

In this paper we consider the “budgeted multi-arm bandit” problem, where exploration and exploitation are decoupled and the agent can only explore for a finite time before deciding which arm to exploit [30].

We study using Gaussian process implicit surfaces (GPIS) to represent shape uncertainty, based on its ability to combine various modes of noise observations such as tactile, laser and visual. GPIS representations model a distribution over implicit surface functions, which are becoming increasingly popular in robotics due to their success in real-time surface modeling from range images [5], [4]. GPIS representations have recently been used in a number of robotic applications. Hollinger et al. used GPIS to perform active sensing on the hulls in underwater boats [7]. Dragiev et al. showed how GPIS can represent shapes for grasps and used as a grasp controller on the continuous signed distance function

[6]. Mahler et al. used GPIS representation to find locally optimal anti-podal grasps by framing grasp planning as an optimization problem [?]. Sampling from GPIS for grasp quality evaluation is computationally intensive, however, because it involves the Cholesky decomposition of an $m \times m$ matrix which takes $O(m^6)$ time, where m is the dimension for a 2D grid over and object [31].

III. PRELIMINARIES AND PROBLEM STATEMENT

In this section we describe the mathematical derivation of Gaussian Process Implicit Surface representations.

A. Multi-Arm Bandit Problem

The multi-arm bandit problem originally described by Robbins [20] is a statistical decision model of an agent trying to optimize his decisions, while improving his information at the same time. In a multi-arm bandit problem the gambler has K independent slot machine arms and tries to infer, which one will yield the highest return. A good gambler would want to exploit the machine that currently yields a high reward and explore new machines to see if he can better his chances. Developing a policy that successfully does this trade has been the focus of extensive research, since the problem formulation [32][20] [33].

There is a number of algorithms for developing policies to balance exploration and exploitation. Algorithms that have theoretical guarantees are based on UCB [TODO: DESCRIBE UCB]. Those that are derived from empirical methods are developed off of the ϵ -greedy approach. ϵ -greedy is the idea of choosing the arm with the current best expected value with $1 - \epsilon$ probability and choosing a different arm with probability ϵ . [18]. In practice, when the distribution on the arm is not in closed form, like not in the exponential family, the empirical methods have shown to have better performance [34].

In the problem of choosing the best grasp, one must intelligently allocate samples based on the observations received so far. As you can in Fig. 4, a typical grasp can take hundreds of iterations for convergence of the expected value to be reach. Thus if one had 1000 grasps to choose from, it would take on the order of millions grasp metric evaluations to choose the best grasp in the naive way. If we can develop a policy to intelligently explore the proposed grasps and select the best one, we can reduce the computational complexity of grasping with uncertainty.

[TODO: ADD MULTI ARM BANDIT PRELIMINARY MAKE IT LONG]

B. Gaussian Process (GP) Background

[TODO: MASSIVE TRIM DOWN] GPs provide an infinite dimensional analogue of Multivariate Gaussian Distributions which allow us to model distributions over functions. Gaussian processes (GPs) are widely used in machine learning as a nonparametric regression method for estimating continuous functions from sparse and noisy data [35]. In a GP, a training set consists of input vectors $\mathcal{X} = \{\mathbf{x}_1, \dots, \mathbf{x}_n\}$, $\mathbf{x}_i \in \mathbb{R}^d$, and corresponding observations $\mathbf{y} = \{y_1, \dots, y_n\}$. The

observations are assumed to be noisy measurements from the unknown target function f :

$$y_i = f(\mathbf{x}_i) + \epsilon, \quad (1)$$

where $\epsilon \sim \mathcal{N}(0, \sigma^2)$ is Gaussian noise in the observations. A zero-mean Gaussian process is completely specified by a covariance function $k(\cdot, \cdot)$, also referred to as a kernel. Given the training data $\mathcal{D} = \{\mathcal{X}, \mathbf{y}\}$ and covariance function $k(\cdot, \cdot)$, the posterior density $p(f_* | \mathbf{x}_*, \mathcal{D})$ at a test point \mathbf{x}_* is shown to be [35]:

$$\begin{aligned} p(f_* | \mathbf{x}_*, \mathcal{D}) &\sim \mathcal{N}(\mu(\mathbf{x}_*), \Sigma(\mathbf{x}_*)) \\ \mu(\mathbf{x}_*) &= k(\mathcal{X}, \mathbf{x}_*)^\top (K + \sigma^2 I)^{-1} \mathbf{y} \\ \Sigma(\mathbf{x}_*) &= k(\mathbf{x}_*, \mathbf{x}_*) - k(\mathcal{X}, \mathbf{x}_*)^\top (K + \sigma^2 I)^{-1} k(\mathcal{X}, \mathbf{x}_*) \end{aligned}$$

where $K \in \mathbb{R}^{n \times n}$ is a matrix with entries $K_{ij} = k(\mathbf{x}_i, \mathbf{x}_j)$ and $k(\mathcal{X}, \mathbf{x}_*) = [k(\mathbf{x}_1, \mathbf{x}_*), \dots, k(\mathbf{x}_n, \mathbf{x}_*)]^\top$. This derivation can also be used to predict the mean and variance of the function gradient by extending the kernel matrices using the identities [36]:

$$\text{cov}(f(\mathbf{x}_i), f(\mathbf{x}_j)) = k(\mathbf{x}_i, \mathbf{x}_j) \quad (2)$$

$$\text{cov}\left(\frac{\partial f(\mathbf{x}_i)}{\partial x_k}, f(\mathbf{x}_j)\right) = \frac{\partial}{\partial x_k} k(\mathbf{x}_i, \mathbf{x}_j) \quad (3)$$

$$\text{cov}\left(\frac{\partial f(\mathbf{x}_i)}{\partial x_k}, \frac{\partial f(\mathbf{x}_j)}{\partial x_l}\right) = \frac{\partial^2}{\partial x_k \partial x_l} k(\mathbf{x}_i, \mathbf{x}_j) \quad (4)$$

For our kernel choice we decided to use the square exponential kernel, a major reason for this was its differentiability. Other kernels relevant to GPIS are the thin-plate splines kernel and the Matern kernel [37].

We construct a GPIS by learning a Gaussian Process to fit measurements of a signed distance field of an unknown object. Precisely, $x_i \in \mathbb{R}^2$ in 2D and $x_i \in \mathbb{R}^3$ in 3D, and $y_i \in \mathbb{R}$ is a noisy signed distance measurement to the unknown object at x_i .

C. Line of Action

Similar to the work of [2], we assume that each gripper finger approaches along a *line of action*, a 1D curve $\gamma(t)$ with endpoints a and b as seen in Fig. 3. A gripper finger starts at point a and moves towards b , we assume a is far enough away to be collision free of the object. Each gripper contact is defined by a line of action, so we assume the following tuple is provided $\Gamma = (\gamma_1(\cdot), \dots, \gamma_m(\cdot))$, which designates a proposed *grasp plan*. While we currently assume the gripper moves free of noise, this approach would be applicable to high precision robots such as industrial based on. Future work will look at how to efficiently sample when the approach trajectory has noise.

D. Problem Definition

Given a 2-D workspace \mathcal{W} , with an unknown object represented as a trained GPIS model and set of possible grasp plans G . We are interested in determining

$$\Gamma^* \in \text{argmax}_{\Gamma \in G} E(Q(\Gamma)) \quad (5)$$

with respect to a chosen grasp metric Q .



Fig. 2: Six example objects illustrating transparency, specularity, sensor noise that illustrate the need for shape uncertainty: (from top to bottom) tape, squirt bottle, stapler, loofa, marker, water bottle. Displayed from right to left are the HD color image, a point cloud observation from a Primesense Carmine, GPIS visualization technique from [?], the nominal shape on a 25×25 grid.

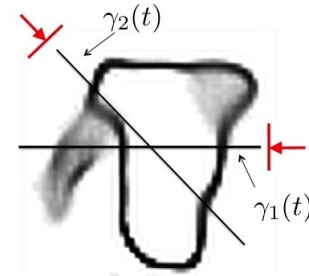


Fig. 3: Illustration of a grasp plan Γ composed of two lines of action, $\gamma_1(t)$ and $\gamma_2(t)$

IV. ADAPTIVE SAMPLING FOR GRASP SELECTION

After determining how to efficiently compute the $E(Q(\Gamma))$, we need to now compute the full problem of Eq. 5, hence the selecting the best grasp plan Γ^* . While a standard approach to solving this problem would be to simply perform Monte-Carlo integration on each Γ_i and compute the

expected grasp quality, we propose treating the problem as a multi-arm bandit problem and forming a policy for selecting which grasp to sample. The motivation behind this is due to the expensive evaluation that our grasp metric Q can take [38] and the fact that the convergence of the expected quality of a typical grasp can take hundreds of evaluations as shown in Fig. 4.

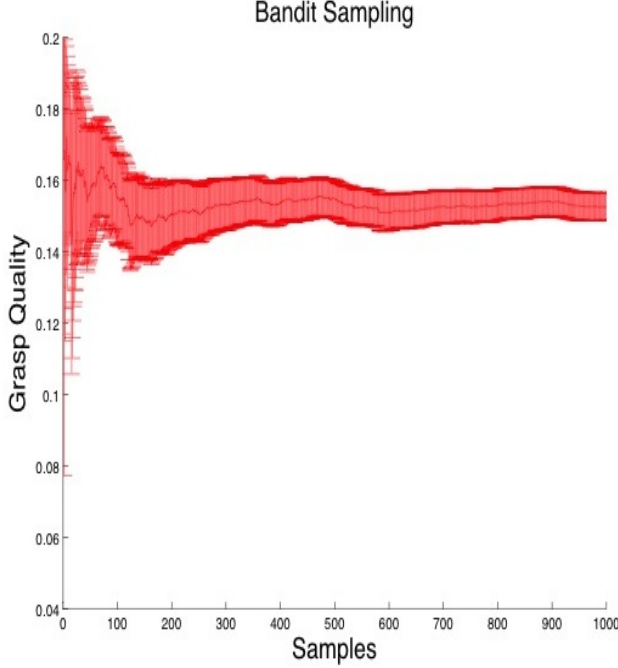


Fig. 4: Convergence of expected grasp quality, $E(Q(g))$, for a typical grasp. You can see it can take hundreds of evaluations to correctly estimate the expected grasp quality, thus it is important to intelligently allocate sampling resources

A. Preliminaries

Motivated by limited computational resources we are interested in how to intelligently allocate sampling resources to efficiently find the best grasp plan Γ^* . We can formulate this problem as a “budgeted multi-arm bandit problem” [30]. We have a policy for exploration of different grasp plans (i.e. choosing which one to sample next) and at a given stopping time we choose to execute the grasp plan with the highest expected quality based on the samples received so far.

We measured performance of our policies in terms of simple regret, which is the difference of the true expected value of the actual best grasp plan and the true expected value of the selected grasp plan at the given stopping time [32]. The number of samples needed before the simple regret reaches zero, determines how effective an exploration policy is for grasp evaluation.

B. Our Implementation

In solving Eq. 5, we want to pick the grasp plan with the highest $E(Q(\Gamma))$ determined via Monte-Carlo Integration. Due to the non-linear nature of our grasp metric, we currently do not have a way to represent the distribution on grasp quality of $p(Q(\Gamma))$ in closed form. Thus, we are

restricted in the type of bandit policies available to us, since most sophisticated policies require distributional information. [TODO: DOUBLE CHECK WITH DYLAN]

For our exploration policy, we maintain a subset of the possible grasp plans that are statistically indistinguishable from the best grasp plan. During exploration, we sample uniformly from this subset. This has been shown to have good performance when the number of evaluations is large [32]. For each grasp plan, we maintain a 95% confidence interval around the expected quality of the grasp plan. The width of the confidence interval for a grasp plan i that has been sampled n_i times and the samples have standard deviation σ_i is:

$$C_i := \frac{1.96\sigma_i}{\sqrt{n_i}}. \quad (6)$$

Let $\hat{\mu}_i$ be the sample mean of the grasp quality for grasp plan i . Thus the confidence interval for grasp plan i is $[\hat{\mu}_i - C_i, \hat{\mu}_i + C_i]$ [15]. After a sample from a grasp plan, we check to see if the confidence interval of the sampled grasp intersects with the confidence interval of the current best grasp plan, and if it does not, we prune that grasp plan from the current active set of grasp plans. Since we prune grasps that are below a confidence interval we have statistical guarantees unlike earlier approaches to this problem[8]. In future work, we will look at using other exploration strategies.

V. EVALUATING A GRASP

In order to solve our problem definition, we must evaluate $E(Q(\Gamma))$ for a given grasp plan Γ . We will first discuss which grasp metric Q we chose and then proceed into evaluating the expectation E efficiently.

A. Grasp Metric

In their pioneering work over two decades ago Ferrari and Canny [38], demonstrated a method to rank grasps by considering their contact points and surface normals. Importantly the magnitude of Q yields a measurement that allows one to rank grasps by their physical stability and evaluate the property of force-closure. Furthermore, it has wide spread use in grasp packages like GraspIT[39], OpenGrasp[40] and Simox [41], which motivates studying its effect with uncertainties.

The L^1 version of the metric works by taking as input the contact points $\mathbf{c}_1, \dots, \mathbf{c}_m$, surface normals $\mathbf{n}_1, \dots, \mathbf{n}_m$, center of mass \mathbf{z} and friction coefficient μ . Then constructing a convex hull around the wrenches made up of those parameters and finding the radius of the largest unit ball centered at the origin in wrench space. A wrench is defined as concatenation of a force and torque vector. If the convex hull doesn’t enclose the origin, the grasp is not in force-closure. Thus a grasp can be parameterized by the following tuple $g = \{\mathbf{c}_1, \dots, \mathbf{c}_m, \mathbf{n}_1, \dots, \mathbf{n}_m, \mu, \mathbf{z}\}$, our method is applicable to all grasp metrics that represent a grasp as the tuple g , such as [2], [42].

B. Calculating the Expected Grasp Quality

Given a proposed grasp plan Γ , the expected grasp quality can be evaluated as follows:

$$E(Q(\Gamma)) = \int Q(g|S, \Gamma) p(S) dS \quad (7)$$

Where $Q(g|S, \Gamma)$ is the grasp quality that is computed on a shape sample drawn from $p(S)$. To compute this we intersect the zero crossing of the level set with the proposed grasp plan Γ and determine the parameters g , this has been the approach taken in previous work [1], [8], [2]. See Fig. 5 for an example of what samples drawn from $p(S)$ induced by GPIS look like. For computational reasons we approximate the integral via Monte-Carlo Integration. We use importance sampling to draw from the distribution induced by GPIS and calculate the following

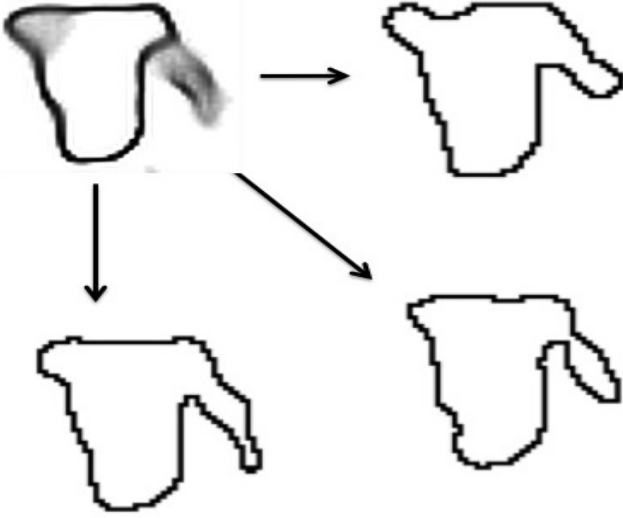


Fig. 5: Shape samples drawn from Eq. 8 on the object in the upper left corner. Given a shape sample we highlight the zero-crossing of the level set in black

$$E(Q(\Gamma)) \approx \frac{1}{N} \sum_{i=1}^N Q(g|S_i, \Gamma), \quad S_i \sim p(S)$$

To compute the above distribution we must draw samples from $p(S)$. In order to draw shape samples from a GPIS, one needs to sample from signed distance function, sd , over the joint on all points in the workspace \mathcal{W} or $p(sd(\mathcal{W}))$. Since this is a GPIS, we know the following

$$p(S) = p(sd(\mathcal{W})) \sim N(\mu(\mathcal{W}), \Sigma(\mathcal{W})) \quad (8)$$

Thus if the workspace is an $n \times n$ grid, the joint distribution is an n^2 multi-variate Gaussian, due to $sd : \mathbb{R}^2 \rightarrow \mathbb{R}$. Sampling from a Gaussian involves inverting the covariance matrix and inversion is in the naive way $O(n^3)$ [43]. Thus the complexity of this operation is $O(n^6)$ in 2D and $O(n^9)$ in 3D.

To reduce complexity we propose sampling not from the shape distributions, but instead from the distributions on the grasps parameters themselves. We recall that a grasp according to our metric is defined as the tuple $g = \{\mathbf{c}_1, \dots, \mathbf{c}_m, \mathbf{n}_1, \dots, \mathbf{n}_m, \mu, z\}$. We are thus interested in calculating $p(g|\Gamma, \mu(x), \Sigma(x))$. The distribution on a grasp is defined then as:

$$p(g) = p(\mathbf{c}_1, \dots, \mathbf{c}_m, \mathbf{n}_1, \dots, \mathbf{n}_m | \Gamma, \mu(x), \Sigma(x)) \quad (9)$$

We note here that we currently use the friction coefficient μ and the expected center of mass \bar{z} as deterministic values. For grippers that do not approach along the same line of action (i.e. non-parallel jaw grippers) we make the assumption that each contact and normal pair is independent, or

$$p(g) = \prod_{i=1}^m p(\mathbf{c}_i, \mathbf{n}_i | \gamma_i(t), \mu(x), \Sigma(x)) \quad (10)$$

We compute the expected grasp quality now as follows:

$$E(Q(\Gamma)) = \frac{1}{N} \sum_{i=1}^N Q(g_i), \quad g_i \sim p(g) \quad (11)$$

We will now show how these distributions can be computed and how the complexity for evaluating a grasp is reduced from $O(n^6)$ to $O(n^3)$.

VI. DISTRIBUTION OF GRASP PARAMETERS

To sample from $p(g)$, we need to sample from the distributions associated with a line of action $p(\mathbf{n}_i, \mathbf{c}_i | \gamma_i(t), \mu(x), \Sigma(x))$. Using Bayes rule we can rewrite this as

$$p(\mathbf{n}_i, \mathbf{c}_i | \gamma_i(t), \mu(x), \Sigma(x)) = p(\mathbf{n}_i | \mathbf{c}_i, \gamma_i(t), \mu(x), \Sigma(x)) p(\mathbf{c}_i | \gamma_i(t), \mu(x), \Sigma(x))$$

In section VI-A, we look at how to sample from $p(\mathbf{c}_i | \gamma_i(t), \mu(x), \Sigma(x))$. Then in section VI-B, we look at how to sample from $p(\mathbf{n}_i | \mathbf{c}_i, \gamma_i(t), \mu(x), \Sigma(x))$ and present a novel visualization technique for the distribution on surface normals. Lastly in section VI-C, we show a way to calculate the expected center of mass assuming a uniform mass distribution.

A. Distribution on Contact Points

We would like to find the distribution on contact point \mathbf{c}_i . A contact point in terms of the GPIS and line of action model can be defined as the point, t , when the signed distance function is zero and no points before said point along the line have touched the surface. We express this as the following conditions:

$$sd(\gamma(t)) = 0 \quad (12)$$

$$sd(\gamma(\tau)) > 0, \quad \forall \tau \in [a, t) \quad (13)$$

We will now demonstrate how to efficiently sample from $p(\mathbf{c}_i | \mu x, \Sigma x, \gamma_i t)$

The probability distribution along the line $\gamma(t)$ is given by:

$$p(sd(\gamma(t)); \mu(t), \Sigma(t)) \quad \forall t \in [a, b] \quad (14)$$

This gives the signed distance function distributions along the entire line of action in the workspace as a multivariate Gaussian. One could think of this as a marginalization of all other points in signed distance field except the line of action. To sample contact points, one can simply draw samples from Eq. 3 and iterate from a to b until they reach a point that satisfies Eq. 12 and Eq. 13.

B. Distribution on Surface Normals

Using Eq. 3 and Eq. 4, we can compute the mean of the gradient $\mu_{\nabla}(x)$ and the covariance of the gradient $\Sigma_{\nabla}(x)$ respectively. Thus we can compute the distribution around the surface normal for a given point in \mathcal{W} . We can now write

$$p(\mathbf{n}_i | \mathbf{c}_i = \gamma(t)) = p(\mathbf{n}_i | \mu(\gamma(t)), \Sigma(\gamma(t)))$$

One interesting effect of this technique is that we can now marginalize out the line of action model and visualize what the surface normal distribution is along a given line of action. To our knowledge this is the first attempt to visualize surface normals along a grasp plan. Marginalization can be performed as follows:

$$p(\mathbf{n}_i) = \int_a^b p(\mathbf{n}_i = \mathbf{v} | \mathbf{c}_i = \gamma(t)) p(\mathbf{c}_i = \gamma(t)) dt \quad (15)$$

Grasp metrics such as Ferrari-Canny require \mathbf{n}_i be normalized, or, equivalently, a member of the sphere S^{d-1} [38]. To account for this we densely sample from the distribution $p(\mathbf{n}_i)$ and project onto S^{d-1} . In Fig.??, we visualize the theoretical distribution on \mathbf{n}_i calculated for a given GPIS and approach line of action.

C. Expected Center of Mass

We recall the quantity $P(sd(x) < 0) = \int_{-\infty}^0 p(sd(x) = s | \mu(x), \Sigma(x)) ds$ is equal to the probability that x is interior to the surface under the current observations. We assume that the object has uniform mass density and then $P(sd(x) < 0)$ is the expected mass density at x . Then we can find the expected center of mass as:

$$\bar{z} = \frac{\int_{\mathcal{W}} x P(sd(x) < 0) dx}{\int_{\mathcal{W}} P(sd(x) < 0) dx} \quad (16)$$

which can be approximated by sampling \mathcal{W} in a grid and approximating the spatial integral by a sum. Since this operation involves the entire SDF, one would want to use a low resolution grid for computational efficiency. We show the computed density and calculated expected center of mass for a marker in Fig. 7.

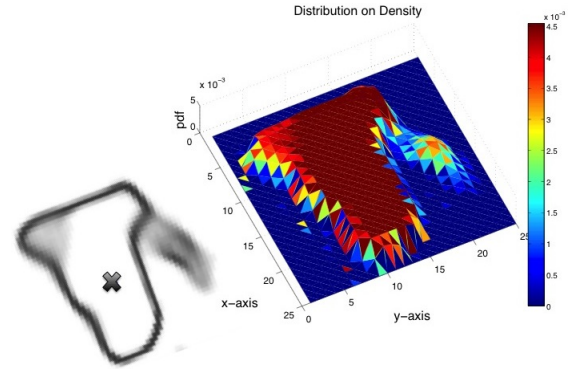


Fig. 7: Left: A surface with GPIS construction and expected center of mass (black X) Right: The distribution on the density of each point assuming uniform density

D. Complexity Analysis on Sampling From Grasps Distributions

After formally deriving each distribution, we can now sample along each line of action $\gamma_i(t)$ from the joint distribution $p(\mathbf{c}_i, \mathbf{n}_i | \gamma_i(t))$, due to our independence assumption Eq. 10. This can be done by drawing samples from Eq. ?? and using our projection technique for the normal distribution.

Having a distribution along a line of action model allows us to sample from those instead of the joint distribution $p(sd(\mathcal{W}))$. Assuming the line of action is on the order of n , sampling from this distribution for a single grasp is $O(n^3)$. However, each proposed grasp plan Γ requires the distribution to be computed, so if we have $T = |\mathcal{G}|$ then the complexity is $O(Tn^3)$. In practice, this should be much smaller than $O(n^6)$.

VII. EXPERIMENTS

For the experiments below we used common household objects shown in Fig. 2. We manually created a 25 x 25 grid, by tracing a pointcloud of the object on a table taken with a Primesense Carmine depth sensor. To accompany the SDF, we created an occupancy map, which holds 1 if the point cloud was observed and 0 if it was not observed, and a measurement noise map, which holds the variance 0-mean noise added to the SDF values. The parameters of the GPIS were selected using maximum likelihood on a held-out set of validation shapes. Our visualization technique follows the approach of [?] and consisted of drawing many shape samples from the distribution and blurring accordingly to a histogram equalization scheme.

We did experiments for the case of two hard contacts in 2-D, however our methods are not limited to this implementation. We drew random lines of actions $\gamma_1(t)$ and $\gamma_2(t)$ by sampling around a circle with radius $\sqrt{2}n$ and sampling the circles origin, then projecting onto the largest inscribing circle in the workspace.

A. Sampling from Grasps Vs. Shape

We first tested 1000 grasp plans and sampled each one 5000 times and measured the RMS error between converged expected grasp plan qualities for sampling shape Eq. 7 vs. grasps Eq. 11 was 0.004. After confirming the distributions

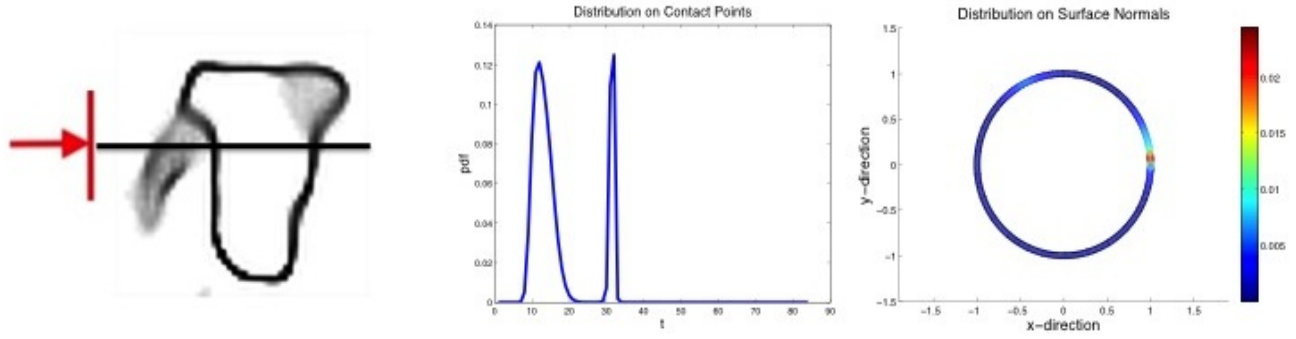


Fig. 6: (Left to Right): Line of action for a given gripper on an uncertain surface representing a measuring cup. Distribution $p(c)$ as a function of t , the position along the line of action $\gamma(t)$. The two modes correspond to the different potential contact points, either the handle or the base of the cup. Lastly, the distribution on the surface normals (inward pointing) along $\gamma(t)$ described by equation ??.

converged close to the same value, we show the computational complexity in Fig. 8 of the two methods for evaluating 100 grasps on an $n \times n$ grid.

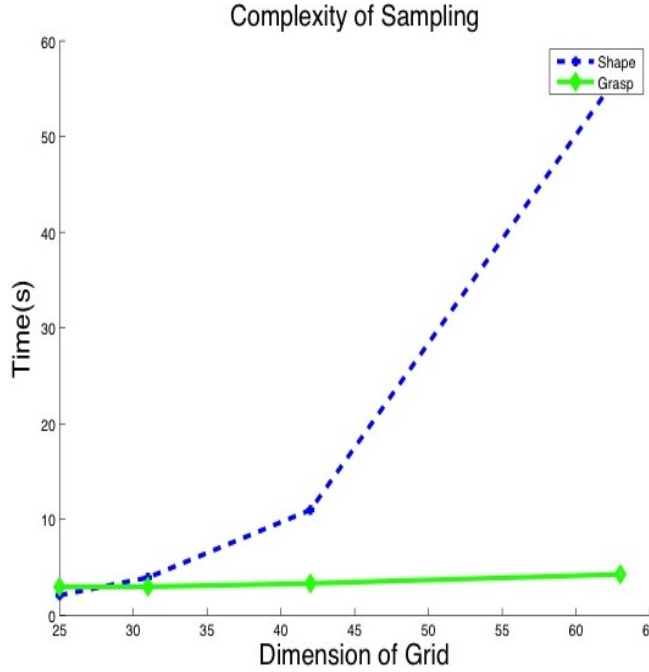


Fig. 8: Time it took to sample from 100 grasp distributions for a given resolution of the workspace. Blue line is sampling from $p(sd(\mathcal{R}))$ or shapes and Green is sampling from $p(g)$ or the calculated distribution on grasps. As you can see sampling from the calculated distributions scales much better.

B. Adaptive Sampling Technique

We consider the problem of selecting the best grasp out of a set G given a fix number of iterations I . For our experiments we look at selecting the best grasp out of a size of $|G| = 1000$ and $I = 7000$ or when the set of grasps is a single grasp. In Fig. 9, we plotted the simple regret, Eq. ??, averaged over 20 runs and compare it to the naive Monte-Carlo method that randomly chooses a grasp plan to draw a sample from . The most interesting thing is that the regret is minimized an order of magnitude faster than the naive approach, thus motivating the use of including observations as you select samples.

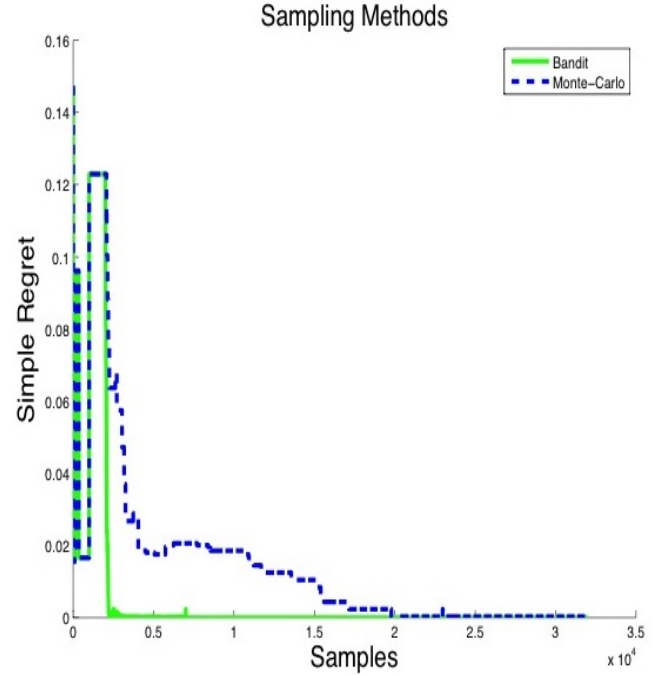


Fig. 9: Comparison of two sampling methods. Green is the adaptive bandit method that actively chooses which one to sample and Blue is the naive Monte-Carlo method. We measure their ability to converge in terms of simple regret Eq. ?? averaged over 100 runs. We had them determine the best grasp when $|G| = 1000$. As you can see our method converges much faster with an average of evaluation of 4 samples per grasp. We start the process though by deterministically evaluating every grasp 2 times to achieve a baseline, which explains the first part of the graph.

VIII. LIMITATIONS AND FUTURE WORK

Sampling from our distribution $p(g)$ over $p(S)$ yields a reduction in computational complexity, but only if the number of grasps one wants to evaluate remains small relative to n^3 , techniques to ensure this could be to find locally optimal potential grasps using optimization approaches [?].

An additional problem is that we only have an expected center of mass and not a distribution on the center of mass. This might prove to be too expensive to compute, however recent work by Panahi et al. showed a way to bound the center of mass for convex parts. Extension of his work to implicit surfaces could be of possible interest [44].

Our budgeted multi-arm bandit approach appears promis-

ing, but we still do not know how well it will perform on 3D shapes and large scale grids. Future work will be building an efficient construction of GPIS to scale to 3D. Lastly, we are interested in investigating how well our algorithm works in parallel computing to be used in the cloud computing context. Furthermore, there is a large literature on formulating bandit policies and experimenting with them all will need to be done to see which one works best.

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