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Active tactile exploration with uncertainty and travel cost for fast shape estimation of unknown objects

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HIGHLIGHTS

- Active tactile exploration for object shape estimation.
- Consider uncertainty of estimated shape and travel cost to touch for fast estimation.
- Combine Gaussian process implicit surface with a graph-based path planning.
- Results indicate faster estimation as compared to comparisons.

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ABSTRACT

In this paper, active tactile exploration for object shape estimation is explored. A prior work suggested to touch the most uncertain part of the estimated shape for minimizing the required number of touches. In this paper, it is pointed out that it may not be the best approach for fast estimation. We propose a novel criterion in active touch point selection for fast estimation, which considers both uncertainty of shape estimation and travel cost to touch. Our method employs a Gaussian process implicit surface model to learn the object shape from tactile information, which allows us to evaluate the uncertainty of the shape estimation with an analytic form. To estimate the travel costs for all the touch candidates, our method utilizes a computationally-efficient graph-based path planning method based on stochastic optimal control theory. Simulations with 2D and 3D objects and real-robot experiments with a 7DOF robot arm and a single finger device equipped with a tactile sensor are conducted. Experimental results verify the effectiveness of our method for fast tactile object shape estimation as compared to passive exploration and active exploration that touches the most uncertain part of the estimated shape.

1. Introduction

Real world robots in our daily living environment are required to interact with several tools and objects. To manipulate and handle them, such shape information is important. However, it is not given a priori, and assuming total knowledge in advance is unrealistic. Therefore, developing the capability for such robots to estimate the shape of an unknown object by only using their own sensor modalities is crucial. In particular, tactile sensing is a key ingredient for object shape estimation. Since vision sensors are noisy and suffer from occlusions, the touch-to-sense approach is beneficial for complementary obtaining local but accurate shape information of objects.

Existing works in tactile object shape estimation can be categorized into two groups: *shape discrimination* and *shape estimation*. In shape discrimination, the objective is to identify the most suitable shape of an unknown object among a finite set of candidates based on tactile data obtained through touches. Schneider et al. proposed an object identification method with tactile sensors using bag-of-features [1]. Lepora et al. adopted a statistical method for shape and position discrimination [2]. Those studies focused on the feature extraction or perception methods for object shape discrimination. Thus, touches (actions) to obtain tactile information are rather naive; pre-designed touches are repeatably/sequentially carried out. Experimental studies suggested that humans *actively* utilize six different primitive behaviors and its variants, so-called exploratory procedures (EPs) when they explore the object's properties by haptics [3,4]. Its quantitative analysis [5] and optimal integration to visual perception are also studied in [6,7]. Active selection of exploratory actions can improve the discrimination accuracy even with short-time exploration. Tanaka et al. [8] proposed an active exploration framework with continuous exploratory actions by combining an active learning scheme [9] with unsupervised learning. Aggarwal et al. [10] explored active tactile object recognition in under water environment. A potential drawback of

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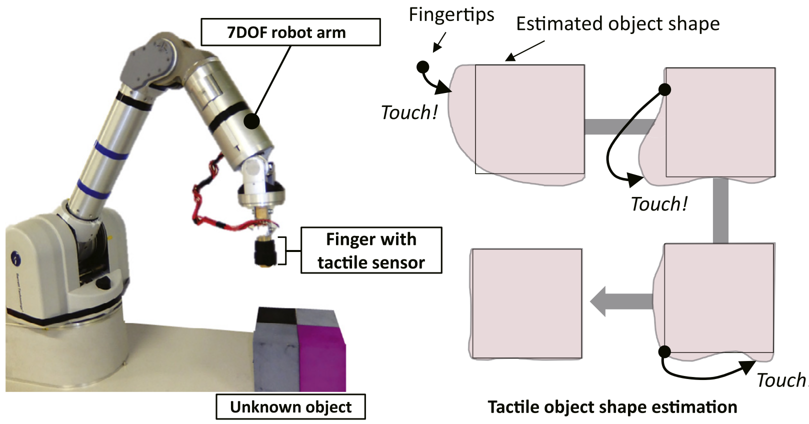

Fig. 1. Overview of our tactile object shape estimation system for 2D shape of 3D objects (i.e., shape of bottom surface of a right prism). It is composed of a 7DOF robot arm and a single fingered device with a omnidirectional 2D tactile sensor. Tactile exploration strategy selects next touch point for fast and accurate shape estimation.

this approach is that it may be inapplicable for estimation of novel shapes.

In shape estimation, the objective is to construct a 3D shape representation of an unknown object by tactile sensor data, possibly with other sensor modalities [1,11–14]. Several methods were proposed based on Kalman filter [15,16] and dynamic potential fields [14] to build 3D objects shape model from contact point clouds. Maldonado et al. [17] used a proximity sensor to scan the unseen parts of an object by a depth camera. Faria et al. built contact point clouds as a 3D shape model in an exhaustive way [18]. Okamura et al. [19] investigated a simple strategy with rolling and sliding to explore the object shapes. Martinez-Hernandez et al. [20] developed an active contour-following strategy based on active Bayesian perception [21,22]. Li et al. also explored similar contour-following strategy based on the notion of tactile servoing [23]. Dragiev et al. [13] included laser data in addition to haptic measurements. Their method employs the Gaussian Process Implicit Surface (GPIS) [24] for representing the object shape because it can be applied for a variety of objects (convex/non-convex) and allows us to efficiently evaluate the uncertainty of the shape estimation. Since executing exhaustive touches to completely explore the whole object shape is time consuming, actively selecting touch positions that effectively contribute to shape estimation is more practical for fast shape estimation [25]. A few studies have been conducted in active tactile exploration of 3D shape of unknown objects. Mazzini et al. [26] developed an active exploration strategy and applied it to oil well surface modeling. Björkman et al. [12] developed an active exploration method based on GPIS that touches the most uncertain part of the estimated shape. They demonstrated that such an approach effectively reduces the required number of touches to obtain the whole 3D object shape. One obvious advantage over the shape discrimination is that it is applicable even for novel object shape. However, a considerably large number of touches may be required as compared to the shape discrimination.

In this paper, the approach of tactile object shape estimation is further investigated; a method of active touch-point selection for the fast shape estimation of unknown objects is proposed. For touch-point selection, we propose to use a criterion that considers both the uncertainty of the shape estimation and the travel cost. The uncertainty of the shape estimation has been used as a criterion for active tactile exploration in [12]. However, the number of touches may not be the best objective to be minimized for active touch-point selection for fast estimation because it might require an unnecessarily long travel distance: this would result in an unreasonable execution time, as suggested by Caselli et al. [27]. They proposed such a criterion for tactile shape estimation, that takes both the uncertainty and the travel distance required for the touch into account. Although their experimental results considerably reduce the travel distance and quicker the robot's execution of the estimation, their method is limited to only convex objects. Thus, we aim to develop a method that does not have such a limitation and is applicable for a variety of object shapes.

Our method employs GPIS to model of object shape following [12,13]. To estimate the travel costs for all the touch candidates, our method uses a computationally-efficient graph-based path planning method based on stochastic optimal control theory [28,29]. Therefore, our method can be considered an extension of a previous work [12] by combining a path planning method for faster object shape estimation by a robot to enhance its effectiveness. To verify the effectiveness of our proposed method, we conducted a series of simulations with convex and non-convex 2D and 3D objects. Furthermore, real robot experiments are also conducted with a 7DOF anthropomorphic arm with a single finger device with an omnidirectional tactile sensor for 2D shape estimation of 3D objects (i.e., shape of the bottom surface of a right prism), as shown in Fig. 1. All the simulation and experimental results with several comparisons verify the effectiveness of our method.

A similar approach has been explored by Tosi et al. [30] in the different context of object localization. They considered the trade off between reducing the uncertainty and the execution time in the active touch strategy to localize objects rather than estimating their shape. Thus, the proposed algorithm cannot be directly used for object shape estimation.

In summary, the contributions of this paper can be listed as follows:

- A novel criterion for active touch point selection is proposed, which considers both uncertainty of shape estimation and travel cost to touch for fast tactile object shape estimation.
- Our method extends a state-of-the-art touch point selection method [12] by combining a path planning method for faster object shape estimation.
- Exhaustive simulations with 2D and 3D objects and real-robot experiments are conducted and experimental results verify the effectiveness of our method as compared to passive exploration and active exploration that only considers the uncertainty of the estimated shape [12].

A preliminary result of this work was presented in [31]. However, it was only limited to the shape estimation of 2D objects due to high computational cost. In this paper, an extended method that can be applicable even for 3D objects is presented as explained in Section 2.5. Furthermore, the effectiveness of the method is completely verified by a comprehensive analysis of simulation and experimental results.