Development of Probabilistic Models for Real-Time Perception of Geometric Features with a Sensorized Artificial Finger

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***Abstract*— Real-time haptic perception of objects and their salient geometric features remains a grand challenge for robotics. In this work, probabilistic modeling techniques, widely used for speech recognition, were applied to multimodal tactile sensor data from the haptic exploration of edges. Hidden Markov Models were used to build classifiers to perceive edge orientation with respect to the body-fixed reference frame of an artificial fingertip in real-time. The classifiers required essentially no post-processing of the tactile data, and were robust to differences in fingertip speeds and contact pressures. Preliminary results constitute a promising first step toward real-time decision-making based on haptic perception.**

I. Introduction

Humans use haptic "exploratory procedures" (EPs) to extract object properties using the sense of touch [1]. Geometric features such as curvature, aspect ratio, and edge orientation can be extracted using EPs such as whole hand enclosure and contour following. Haptic perception often enables object identification through touch alone [2].

Previously, we developed a support vector regression model to perceive edge orientation with respect to a body-fixed, fingertip reference frame [3]. With multimodal data from a bio-inspired tactile sensor (BioTac, SynTouch LLC), the support vector regression model was able to perceive edge orientation with accuracies similar to that of the human finger [3]. However, one limitation of the model was that it required some degree of post-processing; carefully constructed temporal "windows" of sensor data had to be extracted and further processed to yield model inputs. Post-processing of the sensor data makes it difficult to implement these models in real-time decision-making applications, such as contour-following of object features at human-like speeds.

In this work, we develop Hidden Markov Models (HMMs) that can be used as a foundation for real-time decision-making. HMMs have been applied extensively in speech recognition applications and have been successfully used to model temporal data [4]. Importantly, HMMs enable the modeling of observations generated by stochastic processes where the states are hidden. HMMs also enable perception updating as new observations are collected. Thus, one might be able to identify the orientation of an edge, for example, before an EP has been completed and without the need for post-processing the sensor data.

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II. Methods

A. Experimental apparatus

A subset of multimodal sensor data from [3] were used in this study. Briefly, the data were collected using a robot testbed consisting of a Whole Arm Manipulator and BarrettHand (Barrett Technology, Cambridge MA) in which a single digit had been outfitted with a BioTac sensor. The artificial fingertip was used to haptically explore a 0.4 cm thick blade using pre-planned trajectories. The edge was randomly oriented at angles ranging from -90° to 90° in 1° increments using the angle definition shown in Fig. 1a. A radial to ulnar stroke (Fig. 1, excerpted from [3]) was conducted at fingertip speeds of 2 and 4 cm/s, and at two contact pressures that can be considered low and high.

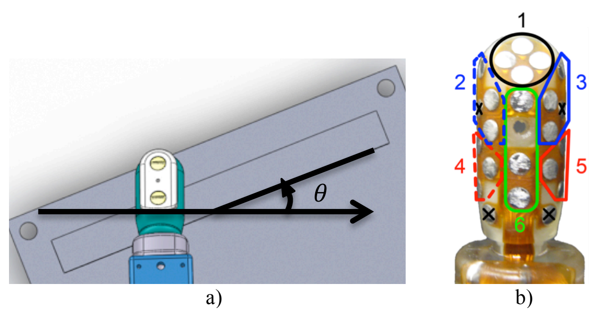

Figure 1. From [3], a) The arrow indicates the radial to ulnar motion of a right-handed index finger across a thick blade that is at an angle of θ with respect to a body-fixed fingertip reference frame. b) The BioTac sensor electrodes were clustered into 6 regions of the fingertip.

B. Processing of tactile sensor data

The BioTac contains 19 electrodes, sampled at 100 Hz, which can be used to extract information about the elastomeric skin deformation relative to the rigid sensor core. As in [3], the electrodes were clustered into 6 groups based on fingertip location (Fig.1b). In this study, we did not use specific temporal windows of data to extract model inputs. Rather a 12-element vector was constructed for each timepoint (in 10 ms increments) that consisted of mean impedance and differential changes in mean impedance for each of the six clusters

C. Hidden Markov Model parameters

An HMM is a Markov chain in which the observations are conditionally independent of other observations given the current state. HMMs are specified by a transition matrix, belief matrix, and an initial state distribution. The transition

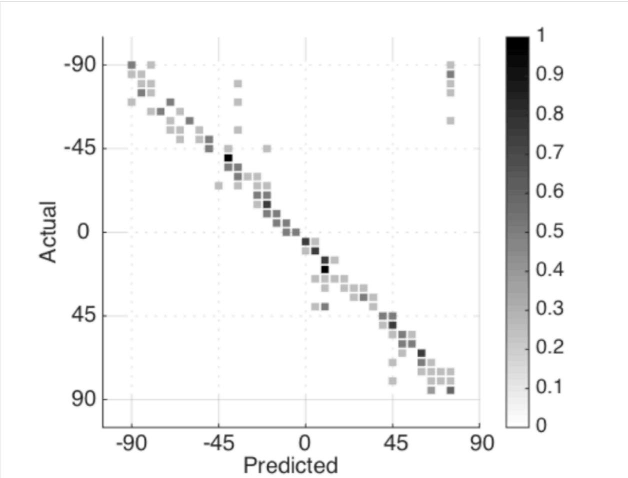

Figure 2. Confusion matrix for an 8 state classification model applied to a test data set.

matrix is the probability of transitioning to a state given the current state. The belief matrix is a mixture of Gaussians that contains the probability of an observation (6 mean impedance and 6 differential changes in mean impedance values) given the current state.

The state of an HMM is an abstraction of the feature space of the data. To avoid overfitting of the model, it is necessary to limit the number of states. In this work, we investigated the effects of the number of states on model performance. Nine different classification models were examined, with states ranging in number from 2-10.

A total of 1445 data samples were used from [3]. A threshold on the internal fluid pressure of the BioTac sensor was used to define the start and end of contact between the fingertip and the edge stimulus. The [-90°, 90°] range of edge orientation angles was split into 36 equally sized 5° increment bins. Thus, for each classification model, a total of 36 independent HMMs were built (one HMM per bin). Within each bin, 90% of the data were randomly selected for a training set, and the remaining 10% of the data were reserved for testing of the classification model.

Each of the HMM's belief and transition matrices were initialized with a random training observation from each bin. The initial state distributions were set to one for the first state and zero for all others. The models were then run through the Baum-Welch algorithm, which adjusts model parameters based on expectation-modification [4]. At each incremental timepoint for a given datastream that includes all data from the initial contact threshold, the classifier determined the most likely bin based on which bin-specific HMM yielded the maximum log-likelihood value. Each of the 9 classification models was tested with a novel dataset.

III. Results & Discussion

The 8-state model performed the best with probabilities of 0.35 and 0.81 for accuracies of $\pm 2.5°$ (one bin) and $\pm 12.5°$ (one bin ± 2 bins), respectively (Fig. 2). The 6-state model produced the highest probability of 0.90 for an accuracy of $\pm 12.5°$. Large prediction errors tended to be near -90° and 90° (Fig. 2). It may be that a radial to ulnar stroke against the thick blade generated similar sensor data for the -90° and 90° orientations, which would make these angles appear similar to the classification model.

While these preliminary probabilistic models could be improved, the results constitute a promising first step toward real-time decision-making based on haptic perception. Real-time calculations of log-likelihood for a given model are on the order of N^2T where N is the number of states and T is the length of the datastream [4]. Modern processors are more than capable of determining log likelihood in real-time. It should be noted that the bin-specific HMMs were robust to differences in fingertip speed and contact pressure. Using a single HMM per bin reduces the computational expense of the log-likelihood calculations and speeds up the classification process. Prediction accuracy would likely improve with a more comprehensive training dataset, additional tuning of model parameters such as observation window size, and modification of model prior distributions.

IV. Conclusions & Future Work

In this study, HMMs were used to develop models that can classify edge orientation relative to a body-fixed, fingertip reference frame in real-time. Such models could be used as a foundation for contour following at human-like speeds. Future work includes expanding the probabilistic models beyond edge orientation and adding models for other salient geometric features, such as bumps and pits [5]. By leveraging probabilistic HMM techniques used in speech recognition for grammar models, we can develop the grammar of haptic exploration.

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