Numerical continuation for edge following in tactile robotics

David A.W. Barton

Department of Engineering Mathematics, University of Bristol, Bristol BS8 1UB, United Kingdom

Summary. Tactile manipulation is a key requirement for future robots if they are ever going to perform delicate but menial tasks such as fruit picking; vision alone is insufficient. Current state-of-the-art tactile sensors require significant amounts of supervised training in order to complete even relatively basic tasks such as edge following, which renders them difficult to use in many situations. This paper explores ideas from the nonlinear dynamics community to address this deficiency by treating the edge following as a numerical continuation problem. Here, the point-wise location of the edge defines a zero problem where the parameters are the position of the tactile sensor.

Introduction

Tactile perception is fundamental to our ability to interact with the environment; without everyday manipulation tasks are far more difficult as the brain is not supplied with the required mechanical contact information [1]. As such, it is reasonable to expect that robots will require some form of tactile sensing before they are able to undertake delicate but menial tasks such as fruit picking [2].

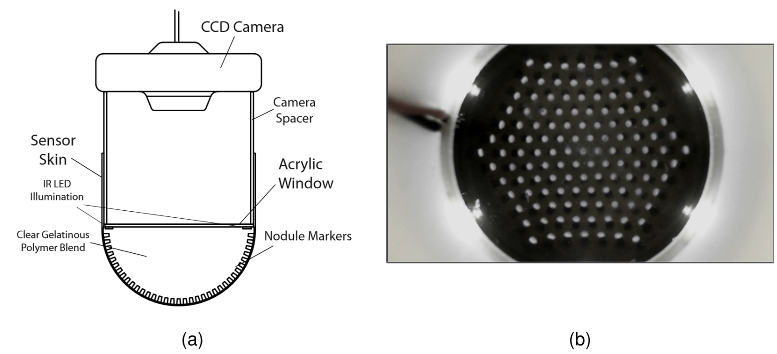
There are a wide range of competing technologies for tactile sensors, ranging from indirect optical sensors and capacitive sensors to whiskered devices [3]. In this study we use the TacTip sensor [4], a low-cost optical sensor that measures the distortion of a flexible membrane as the tactile sensor comes into contact with the surface of interest. The distortion of the membrane is measured via image tracking of small pimples (so-called taxels, reminiscent of the dermal papillae in the human skin) in the membrane surface. A schematic diagram of the TacTip and a photograph of the membrane are shown in Figure 1.

As is common to many tactile sensors, due to manufacturing tolerances, environmental changes and material degradation, the TacTip requires careful calibration against known test data on a relatively frequent basis (often daily, if not more frequently). A typical training approach is to repeatedly bring the TacTip into contact with an edge while varying the distance of the edge to the centre of the TacTip. The recorded timeseries are then used to train a suitable black-box sensor model using an appropriate machine learning algorithm. The sensor model is then used to infer the distance to an edge in future test cases. (Other features, such as edge angle, can trained for and inferred in a similar way.) To achieve a high degree of accuracy, often thousands of training points are used [5] and, as such, training is a significant time investment when using a tactile sensor.

Once a sensor model has been trained, it is then ready to be used for higher-level tasks such as edge following, where the tactile sensor is required to track the edge of an object in space. Such an approach is highly susceptible to variations in the contact point — if the shape or depth of the edge changes, the sensor model will rapidly reach the edge of validity causing the procedure to fail.

Overview

This study considers how these deficiencies in tactile exploration can be overcome using ideas from the nonlinear dynamics community, specifically numerical continuation. Originally it was developed as a means for investigating the bifurcation structure of a mathematical model [6] by means of exploring the structure of an associated zero-problem



(a) (b)

Figure 1: (a) A schematic diagram of the TacTip as it was original envisaged in [4]. (b) A photograph of the inner membrane of the TacTip; tactile interactions are inferred using from the movement of the pimples (taxels) as the membrane deforms.

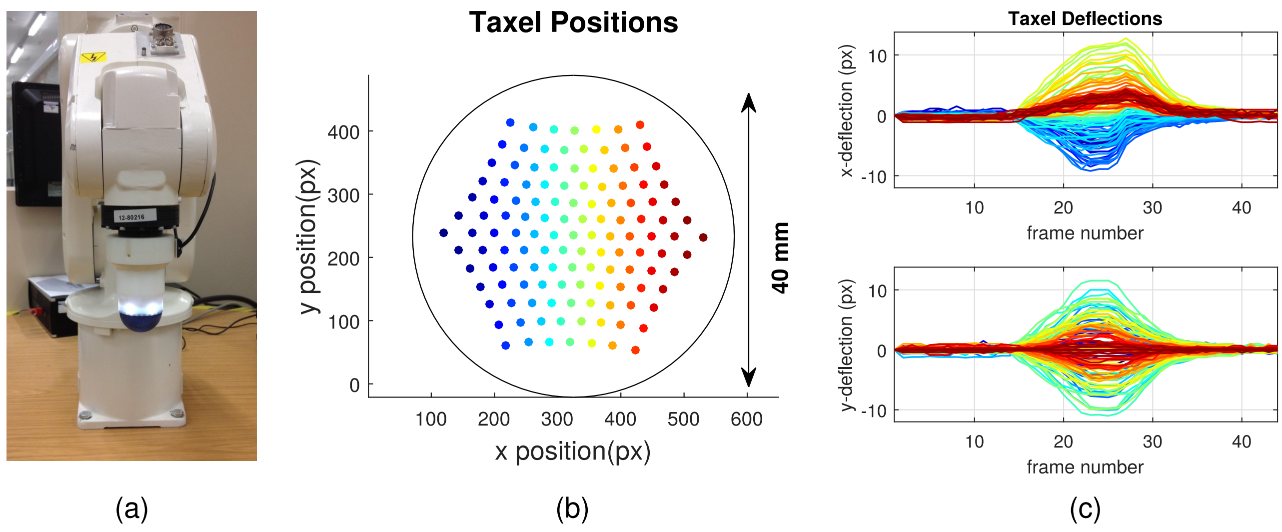


Figure 2: (a) A photograph of a robotic arm with the TacTip attached. (b) A schematic of the taxel positions inside the TacTip. (c) Time series showing the measured deflections of the taxels as the TacTip is used to 'tap' an object.

$f(x, \lambda) = 0$ whereby x is the system state and λ are the system parameters. Numerical continuation has since been extended to tracking limit cycles in physical experiments using so-called control-based continuation [7, 8]. In the case of a physical experiment, the zero-problem is defined implicitly through experimental measurements of the feedback-controlled experiment.

Following the philosophy of control-based continuation, we approach the problem of edge following using a tactile sensor as a numerical continuation problem where the zero-problem is defined indirectly by the experiment. Specifically, we consider the problem of tracking a zero defined by maximising the similarity of the current tactile input to a reference position, subject to certain constraints that are similar in principle to the pseudo-arclength condition often used in numerical continuation. By approaching the high-level problem of edge following in this way, we bypass the need for a low-level sensor model and, hence, avoid the need for extensive (or in deed, any) sensor model training and the failure modes associated with leaving the area represented by the training set.

Figure 2(c) shows the time series of measured deflections of the taxels shown in Figure 2(b). There are 127 taxels, the (x, y) coordinates of which are measured over approximately 45 video frames. The high dimensionality of the data means that the choice of similarity measure is key to the success of the numerical continuation scheme. We will report on the results of edge following using a simple dot-product-based similarity measure and also a Kullback-Leibler divergence-based similarity measure. Furthermore, we will demonstrate the effectiveness of leveraging machine-learning techniques (specifically Gaussian Processes) in the solution of the root-finding problem which lies at the heart of the numerical continuation procedure.

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