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A sequential algorithm for recognition of a developing pattern with application in orthotic engineering

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Abstract

This paper describes an algorithm for the recognition of the type of grip being formed by a subject wearing an intelligent orthotic glove. The signal is a growing multivariate sequence to be correctly classified as soon as the data permit, so the task may be called one of sequential classification or sequential discrimination. The algorithm uses a variant of the 'k nearest neighbours' principle with the dissimilarity measure being an exponentially weighted moving average of distances of the Mahalanobis type. The approach taken seems suitable for other problems of this kind.
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1. Introduction

This paper describes an algorithm for the prediction of the type of grip being formed by subjects with limited wrist, hand or finger function caused, for example, by tetraplegia or stroke. The ultimate goal is the development of an intelligent glove worn to assist the formation of different patterns of grip, e.g., a complex grip for precision or a fist grip for strength. This glove would be able to interpret the initial motions of the fingers as the beginnings of the formation of a certain pattern of grip and then actively direct the subject's fingers into the appropriate pattern while providing extra strength.

One factor distinguishing this problem from many others is the concept that there is human intention at work in the generation of the signal. Nevertheless, there may be many other applications for a *sequential-prediction* or *sequential-classification* algorithm of the kind described, e.g., in remote sensing for classification of moving objects and in the field of condition-based maintenance, where one objective is to detect the onset of a failure in a system as soon as possible.

In tetraplegia, there is partial or complete loss of function in the upper limbs arising from damage to the spinal cord. Damage to the cervical (neck) nerves, especially at or above the C7 vertebra, is likely to result in some loss of control of the fingers in one or both hands. In stroke, neural damage occurring in the brain may also affect control of the fingers. In either case the residual functional ability of the person's hand or fingers varies according to many factors, including the severity of the initial trauma, the efficacy of the treatment during the medical phase of treatment, and the degrees of opportunity and perseverance during the rehabilitation phase. So different people who have had such trauma are left with quite different levels of use of a hand and different ways in which they use their fingers to form grips. Any algorithm for the prediction of intended grip must therefore be customized and not based on a generic model. Our hypothesis is that the most accurate predictions will be obtained by matching the grip being formed at the time of use against entries in a database obtained from that individual. (The term 'database' is used here to denote a list of entries. This usage of the term is not to be confused with that occurring in 'information management'.)

We can summarize the problem as follows. The goal is the development of a glove that measures the beginnings of the

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relative motion between the fingers, predicts the kind of grip being attempted, i.e., classifies the grip, and then directs the subject's fingers into that grip. After each temporal portion of signal is acquired either (i) a classification is made and the glove proceeds to assist in forming the grip or (ii) a classification is deferred pending the acquisition of more data. The figure of 0.3 s maximum before 'activation' of the glove has been suggested; the glove cannot be regarded as a non-intrusive orthosis if the delay is significantly longer than this figure. The algorithm given here has been developed with speed in mind. In this algorithm the intended grip is identified by comparing the signal being acquired with entries in a database known to represent each grip for that person. The 'pattern' to be recognized is the configuration of fingers that the subject is attempting to form.

There are several important differences between this problem and the standard classification problem.

(1) In this problem a classification is sought as soon as possible and is to be achieved well before the motion is completed. We do not wait until all the data have been collected before attempting a classification.
(2) Similarly, in this problem a classification is not to be made until there is sufficient confidence of its accuracy. By contrast, in the standard classification problem the class chosen is simply the one that appears the best. Because there is a fixed amount of data the confidence associated with this best choice does not necessarily reach any predetermined target level.
(3) It is not trivial to compare the signal against the database because the concept of time (which would often provide the natural point of reference) is not immediately relevant. For example, suppose the developing signal at the time of use is a perfect copy of an entry in the database apart from the fact that the grip is being formed more slowly. If the classifier is to register the signal correctly against the database then we must identify a variable that is more suitable than 'time'.
(4) The signal acquired during use ceases to have predictive value after classification because the glove subsequently assists in forming the grip. So there is no growing database on which the classifier might be retrained. That is, we are not acquiring meaningful complete signals during operation and so we are not carrying out *supervised learning*.

Each of these concepts is of substantial significance. Consequently, it is reasonable to expect that an algorithm providing a good solution to the problem will contain elements that are novel. As explained later, our algorithm is based around a variant of the nearest neighbours approach. The measure of dissimilarity employed is derived by forming a moving average of Mahalanobis-type distances [1,2], with the reference variable for this moving average being chosen to be more meaningful than 'time'. Outlying data are removed by a method derived for this application. The full algorithm therefore appeals to standard concepts but introduces modifications to methodology as appropriate. These modifications, which may be of interest in their own right, were developed during the course of this work and are thought to be novel.

As mentioned, the algorithm might also find application in a field such as condition-based maintenance. Likewise, some techniques from that field might be fruitfully applied to this kind of problem; see Ref. [3] for a recent review article. For example, the 'adaptive subspace self-organizing map' (ASSOM) of Ypma et al. [4] bears consideration because of its sequential nature and because it can be made to rely 'on a kind of template matching in the time-domain,' which we shall see corresponds to the basic approach taken here. With the ASSOM there is a 'winning node' after each 'episode' of the data is studied. If the ASSOM were to be adapted for our problem then the focus would need to be shifted from the concept of the 'best choice' to that of a 'sufficiently sure choice'.

One important factor present in our problem but not taken into account in many models is the concept of intention. The signal we seek to classify is the output from a process involving human intention and feedback, both conscious and unconscious. For this reason, the assumption of stationarity cannot be made and the usual stationary time-series models cannot be justified. Also frequency-based and time-frequency-based methods, even if applicable, offer no obvious advantages over time-domain methods because there is no concept of any periodic behaviour in the formation of the grip.

We note the unsuitability of some other popular tools. The pattern to be recognized is the grip being attempted. So we are interested only in predicting a final 'state' and not in a estimating a function or a sequence of states. Therefore the Kalman filter, which attempts to track an unknown function, and the hidden Markov model (HMM), which attempts to recognize a sequence of states, have no clear role in this problem. Moreover, there is no concept here of a finite number of states such as is required in an HMM and there would be no obvious validity in the assumption of a Markov property and, as noted, in the assumption of stationarity.

We defer comments on the statistical technique of principal components until Section 7.

Last, we note various approaches to similar problems. The problem of recognizing grip has also been addressed by Krouse [8], who employs a probability ratio test and a nearest neighbour method using the Fréchet distance between signals [9,10]. The problem of recognizing gestures of disabled people, which involves a stronger sense of a sequence of states, has been addressed by Morrison and McKenna [11] using an HMM. Similarly, the task of programming robots to reproduce grasps demonstrated by humans has been tackled by Ekvall and Kragić [12] using an HMM.

1.1. Concepts of sequential classification

The grip being formed during use of the glove is to be continuously compared against entries in a database until there is sufficient confidence in the identity of the intended grip. The term 'sequential classification' seems relevant to this problem because we are attempting to classify a signal as data are observed sequentially. However, we note that this term does not

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