Chapter 4
Spatio–Temporal Footprints

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ABSTRACT

The recognition of human behaviour from sensor observations is an important area of research in smart homes and ambient intelligence. In this paper, we introduce the idea of spatio-temporal footprints, which are local patterns in space and time that should be similar across repeated occurrences of the same behaviour. We discuss the spatial and temporal mapping requirements of these footprints, together with how they may be used.

INTRODUCTION

A common task that an ambient intelligence system could be required to perform is recognising human behaviour from observations in the environment; this can be useful for a variety of applications from monitoring the activities of elderly patients to identifying appropriate lighting and heating conditions (Cook, 2006; Mozer, 2005). The observations on which such recognition is based can range from direct observations made by video cameras to indirect observations detected by sensors. Although video cameras give a more complete picture, and hence might lend themselves more easily to recognising behaviours (with a consequent increase in the amount of computational processing required), it is often behaviour recognition based on sensors that is the preferred option, since the latter is less obtrusive and therefore more easily accepted in applications such as smart homes.

There is a significant body of research on behaviour recognition based on sensor data, which ranges from logic-based approaches to probabilistic machine learning approaches (Augusto & Nugent, 2004; Chua et al., 2009; Duong et al., 2005; Gopalratnam & Cook, 2004; Rivera-Illingworth et al., 2007; Tapia et al., 2004). Although the reported successes are promising, it has become clear that all approaches fall short of being perfect. Due to
the limited information that is in the sensor data, noise, and the inherently complexity of human behaviours, it is often impossible to determine the correct behaviour from the sensor data alone, in particular if behaviours are overlapping or are being executed by more than one person.

Several researchers have realised that additional information can be useful to boost the behaviour recognition process (Aztiria et al., 2008; Jakkula & Cook, 2008; Tavenard et al., 2007). In this article, we focus on how spatio-temporal information, enriched with context information, can be used for this purpose. When a particular activity occurs, like preparing breakfast, it leaves a ‘footprint’ in space-time, i.e., a particular pattern of sensor observations in some set of locations over some period of time. The activity starts at some specific time and in some specific location, goes on for a specific duration in some specific area, and terminates at a specific time at some specific location. Since footprints differ from behaviour to behaviour—but often relatively little between different instances of the same behaviour—we can use these to inform the behaviour recognition process: if something is happening at 07:00 in the kitchen, it is more likely to be preparing breakfast than taking a shower. We can also use them to detect abnormal behaviour: if the inhabitant of the smart home uses the shower at 03:00 (when usually this is not a footprint that is seen), then this can be interpreted as abnormal.

Figure 1 shows an example of a possible set of footprints over three days, with a linear time axis that repeats each day, and a single space axis that could identify rooms, or similar (this is discussed in more detail in the next section). It can be seen that some behaviours repeat more-or-less identically over the three days, while others only occur once. The challenge with such representation of behaviour as footprints is to identify and recognise the various behaviours that are represented.

The rest of this article investigates the role of spatio-temporal footprints in more detail. We start with a discussion of what space-time means in the context of smart homes, arguing that there is more than one space-time (or more precisely, representation of space-time). We then look at how behaviours leave footprints in space-time and explore invariants in these footprints, with the goal of classifying different forms of invariants. Finally we will look into how the footprints are distributed in space-time and what influences this distribution.

**SPACE-TIME**

When reasoning about time, we usually associate a time axis with the data. The time axis might use a calendar as reference system and absolute dates/times to refer to points on the axis. Or it might use some artificial start point as zero time, such as the time when the smart home became operational, and some counter to advance time along the time axis. In the latter case, we would not be able to refer back to times before the birth of the smart home, while the first case would provide an infinite extension of time into both the past and the future.

As we will see later when discussing footprint invariants, it may sometimes be advantageous to view the time axis as a circular reoccurrence of time points. For example, if we are only interested in when behaviours occur during the day, then we might want to abstract from years, months, and days, which would leave us with references to times of the day. At the end of the day, we would ‘warp’ time and start at the beginning of the time axis again.

Independently of whether we use linear or circular time, we still have to decide whether we view time as continuous or discrete. For example, when referring to 13:00, do we really mean this exact point on a continuous time axis? If this is the case, then a behaviour that occurs one millisecond after this time point would not match 13:00, unless we allow for ‘fuzzy’ matches. On the other hand, if we view it as a discrete time
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