Crowd Textures

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Summary

We are witnessing massive volumes of data about our behavior being produced and collected on a daily basis. This data comprises information about our multitude of activities online, including the World Wide Web and social networking and social media sites, as well a offline, recorded through the myriad of sensors installed in our smart phones and smart watches. Effective modeling and analysis of such data opens the doors to a number of applications and services that are more adaptive and personalized to the user, and to new paradigms like the Internet of Things.

Spatio-temporal proximity is one of the signals that can be captured with existing technology like, for example, radio-based proximity sensors (e.g., Bluetooth Low Energy transceivers in modern smart phones). Spatio-temporal proximity data can be the foundation of a number of analyses of social behavior and in particular, the focus of this dissertation, of crowd behavior. Crowd behavior has a strong spatio-temporal nature, and it lends itself to be studied from this perspective. Furthermore, a crowd is collective in nature, and the behavior of the members of the crowd cannot be understood when looking at the individuals in isolation, but only when the behavior of all the members, together with the relationships, is analyzed. We coined the term "crowd texture" to refer to the interleaved spatio-temporal relationships between the member of a crowd that characterize specific crowd behaviors.

We started our work by interviewing ten crowd managers to understand the current crowd management practices and use of technology. We have found that crowd managers are interested in particular in means of increasing situation awareness, prediction, and intervention, in particular regarding movements and density variations in the crowd (e.g., flows and congestions), but also higher level aspects such as mood, in particular when conditions are critical. We have also found that crowd managers rely on technology only to a limited extent, as the current

existing solutions are found unreliable in most cases. Based on these results, we set as the main research question whether we can leverage spatio-temporal proximity information collected through proximity sensors to gain a better understanding of the behavior of a crowd, to support the work of researchers and practitioners towards safer and more comfortable crowds.

In this dissertation, we model spatio-temporal proximity as a series of proximity graphs, where each graph represents which entities were within a certain range of distance at a specific moment in time. In a proximity graph a vertex represents an entity while an edge represents a positive proximity relationship between two entities. By mining a series of proximity graphs it is possible to identify and quantify different crowd behavior and dynamics, like pedestrian lanes, clogging, social groups, as well as group behavior. Together with the model, we propose a general approach to sense and collect the texture of a crowd though radio-based proximity sensors.

Due to the inherent limitations of wireless sensors networks and radio-based communication, proximity graphs collected with proximity sensors are often noisy and incomplete, meaning that proximity relationships can be wrongly added or missing. Proximity graphs can be filtered to infer the missing relationships and remove the noisy ones. In particular, we present a novel filter based on a density-based clustering algorithm that identifies automatically intervals of proximity between entities in the data, and nearly doubles the accuracy of the measurement. We also present a solution to compute optimal parameters for the technique and we validate it both in simulation and through real-world experiments.

Once proximity data is collected and filtered, it can be analyzed to identify group behavior and gain insight about the behavior of a crowd. We have deployed our infrastructure inside of the CoBrA museum of Amsterdam to track the behavior of some of its visitors (who volunteered to wear one of our sensors), by installing some proximity sensors at exhibits. Working together with the museum staff, we have produced a number of visualizations that helped the museum staff to better understand the amount of time spent by the visitors at each exhibit and the paths within the exhibition rooms followed by them, to name a few examples.

Crowd density is one of the characteristics crowd managers are most interested in, as it can be the cause (or fingerprint) of extreme and dangerous situations. Crowd density is also a major obstacle to radio-based communication, hindering in particular proximity sensing systems that rely on long-range transmissions between wearable sensors and fixed infrastructure. This means that these solutions often fail in the very conditions where they are most needed. We present a solution that leverages mobile-to-mobile proximity sensing to overcome limitations of mobile-to-fixed solutions when crowd density is high. We deployed our solution at the NEMO museum in Amsterdam, a museum located in a complex building characterized by a multi story open space that is particularly challenging for radio-based communication. During our experiment, crowd density at peak was high, with more than 600 visitors wearing our sensor (and overall around 2400 visitors in the museum at that moment). We show that crowd density can be leveraged to increase measurement accuracy as well as to gain insights about the behavior of the visitors.

Spatio-temporal proximity is an effective proxy for measuring crowd behavior, yet it cannot be used to understand higher-level aspects of crowd behavior, which are important to study, for example, mood. In fact, other signals like galvanic skin response, audio and acceleration are more suitable to study the response and the inner experience of the members of the crowd. Still, spatio-temporal proximity can play an important role in these studies, as it can help the understanding of how the response of the crowd (e.g., mood and emotions) spread spatio-temporally across the crowd. We have deployed our proximity sensing infrastructure together with accelerometers that we have used to predict the response of the audience of a dance performance. We show that by measuring proximity and movement of the audience during the performance as well as during mingling sessions before and after the performance, we can predict the enjoyment of the audience.

The work presented in this dissertation shows promising results of the application of pervasive and ubiquitous proximity sensing to the study of social behavior that open a number of new research directions for future work.