Pervasive and Mobile Computing 7 (2011) 319–330

Contents lists available at ScienceDirect

Pervasive and Mobile Computing

journal homepage: www.elsevier.com/locate/pmc

Leveraging human behavior models to predict paths in indoor environments

Bulent Tastan, Gita Sukthankar *

Department of EECS, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816-2362, USA

ARTICLE INFO

Article history:
Available online 2 March 2011

Keywords:
Path prediction
Human tracking
Particle filters

ABSTRACT

One of the most powerful constraints governing many activity recognition problems is that imposed by the human actor. It is well known that humans have a large set of physical and cognitive limitations that constrain their execution of various tasks. In this article, we show how prior knowledge of these perception and locomotion limitations can be exploited to enhance path prediction and tracking in indoor environments for pervasive computing applications. We demonstrate an approach for path prediction based on a model of visually guided steering that has been validated on human obstacle avoidance data. Our approach outperforms standard motion models in a particle filter tracker during occlusion periods of greater than one second and results in a significant reduction in SSD tracking error.

1. Introduction

The ability to predict the path of a moving human is a crucial element in a wide range of applications, including video surveillance, assisted living environments (smart homes), and simulation environments. Two tasks, tracking (finding the user's current location) and goal prediction (identifying the final destination) are particularly relevant to many problems. Human trajectory prediction can serve as a useful supplement to activity recognition in facilitating location-aware user notifications. For instance, recognizing activities of daily living might reveal that the user is engaged in housecleaning; trajectory prediction would enable a home monitoring system to warn the user about a possible tripping hazard. In some cases, predicting the user's trajectory is more important for recognizing user intent than activity recognition; imagine a parking lot surveillance system attempting to match cars to pedestrians. In this case, the recognition that the users are walking would provide comparatively little information relevant to predicting the user's trajectory and/or destination.

Although standard path planning approaches can be used to predict human behavior at a macroscopic level, they do not accurately model human path preferences. In this article, we demonstrate an approach for path prediction based on a model of visually guided steering that has been validated on human obstacle avoidance data. By basing our path prediction on egocentric features that are known to affect human steering preferences, we can improve on strictly geometric models such as Voronoi diagrams [1]. Our approach outperforms standard motion models in a particle filter tracker and can also be used to discriminate between multiple user destinations.

To track humans with sensor networks [2], detect behavior anomalies [3], and offer effective navigational assistance [4], we need to be able to predict the trajectory that a human will follow in an environment. Although human paths can be approximated by a minimal distance metric, humans often exhibit counter-intuitive behaviors; for instance, human paths can be non-symmetric and depend on the direction of path traversal (e.g., humans walking one route and returning via a different one) [5]. Obviously tracking and goal prediction algorithms that assume distance-minimizing behavior will generate errors in environments where the humans' behavior diverges from this model.

* Corresponding author.
E-mail addresses: bulent@cs.ucf.edu (B. Tastan), gitars@eecs.ucf.edu (G. Sukthankar).

1574-1192/$ – see front matter
doi:10.1016/j.pmcj.2011.02.003

To address this problem, we sought a psychologically grounded model of human steering and obstacle behavior to incorporate into our tracking and goal prediction system. Our selected model, originally proposed by Fajen et al. [6] incorporates environmental features that are accessible to the human vision system into a second-order dynamical model; all calculations are based on local perceptual information and do not require global knowledge of the environment. In this article, we demonstrate that a particle filter tracking system based on this human steering model outperforms other commonly used motion models. We trained and evaluated our model in two different scenarios (1) individual subjects navigating an obstacle course in a simulated environment and (2) multiple humans moving around an office environment.

2. Related work

The problem of predicting human trajectories in both indoor and virtual environments has been attacked using a variety of approaches. In the most general version of the problem, human activity recognition, the aim is to characterize or classify the activity performed by the human; specifics such as trajectory either can emerge as a byproduct of the recognition or are utilized as a feature in part of the recognition process. Often this can be treated as a multi-class supervised classification problem as shown by Zhao et al. [7] who demonstrated a set of machine learning techniques to reduce the number of labeled samples required to classify motion capture sequences. However, in some cases, the set of possible activities is not known *a priori* and needs to be discovered in an unsupervised fashion (e.g., [8]).

Interleaved and concurrent activities can be a challenge for the multi-class classification framework; Gu et al. [9] constructed a sensor-based activity recognition system that can recognize such complex activities from sensor data with 78% accuracy from features such as body part acceleration, held objects, and environmental variables. These single-person activity recognition frameworks have also been extended to handle multi-person collaborative activities [10,11]. Even though these algorithms utilize features based on motion data and trajectory information, they do not address the path prediction problem which is the main focus of our research.

Tracking, the problem of predicting where an object or person will be in the immediate future, is often formulated as a state estimation problem and addressed with standard filtering techniques such as Kalman [12] or particle filters [13]. In this case, the problem is to determine the true state of a set of hidden location variables from a sequence of observable sensor data. These state estimation methods rely on having a reasonable motion model for predicting the human's movement; examples of commonly used models include random (Brownian) motion and constant velocity. In more complex state estimation schemes for human transportation routines, the type of motion model can be modeled as a hidden state variable; Liao et al. [14,15] demonstrated a method for tracking and predicting human movements from GPS sensor data in which the mode of transportation (walking, bus, car) was inferred using a hierarchical dynamic Bayes network or conditional random fields [16]. These techniques are more appropriate for movement over long distances and rely on simple velocity models that do not consider angular velocity or acceleration.

In cases where simple velocity and acceleration profiles are not adequate, motion planning methods have been used. Bruce and Gordon [17] introduced a particle filter variant that used motion planning to plan paths to common destinations in the environment; they show this approach to be superior to the standard Brownian motion model for tracking people in cases where the sensor trace is occluded. Voronoi diagrams have also emerged as a popular path planning method for safely avoiding obstacles since a Voronoi path maximizes the distance between the robot and obstacles in the environment [1]. Recently, state estimation models have leveraged Voronoi diagrams for tracking people in indoor environments as a replacement for road networks [18]. Both plan planning and Voronoi motion models are superior to the simpler velocity profiles because they incorporate knowledge of the geometry of the environment (modeled as goals and obstacles) into the path planning. However, these methods are not based on actual human motion profiles, nor are they easily adapted to new subjects. In the next section, we present a steering model that is based on human motion profiles and show how it can be tuned for new subjects. In this article, we only present tracking results from using a particle filter in combination with the steering model, but we believe that we can generalize this approach to other state estimation techniques.

An alternate approach to the global motion planning methods is to assume that the walker makes decisions solely based on local features, without constructing a complete path to the goal. A popular local planning technique, potential-field-based control [19], models the influence of the environment as an imaginary set of attractive and repulsive forces generated from visible goals and obstacles. The walker's direction and speed are determined by the combined influence of the forces. Since potential fields are computationally inexpensive and straightforward to implement, they are a useful steering model for guiding autonomous characters in games and simulations [20]. However, the trajectories generated by a potential-field planner can fail to match human locomotion data, particularly when the planner generates abrupt changes in angular velocity, which is rarely observed in human walkers.

An orthogonal strategy to modifying the motion model is change the sampling procedure. An example of this approach was demonstrated for the problem of hand tracking/gesture recognition by Shan et al. [21] who combined a particle filter framework with mean shift optimization to make particles converge to local peaks while tracking skin colored regions in the video. Following the hand tracking, authors perform gesture recognition by looking backward in time to calculate cell occupancy. Our work is complementary to this type of approach since a better motion model will benefit any type of particle filter tracking and is agnostic to sampling procedure. Occlusions pose a significant impediment to vision-based particle filter trackers; we demonstrate that our particle filter is robust to occlusion. An alternative approach is to construct an explicit model of the occlusion types that can occur during the video sequence; this has been demonstrated by Xu and Ellis [22] for