7 Conclusions and Future Work

7.1 Summary and Contributions

This dissertation describes a novel state transition system approach for modeling a smart indoor environment that can identify and track its occupants unobtrusively and answer queries about their whereabouts. Our model effectively provides support for the basic 3 R’s of a smart environment: recognition (through events), reasoning (through transitions), and retrieval (through states). We also provide a succinct statement of its query-independent and query-dependent performance in terms of information-theoretic concepts of precision and recall. This unified model serves as an elegant basis for integration of recognition and spatio-temporal reasoning capabilities for improved performance over a pure biometrics-based recognition system. A variety of probabilistic spatio-temporal queries are supported by this model.

*State Transition System Model:* In our probabilistic state transition model of a smart environment, events abstract different biometric recognition steps, transitions abstract different reasoning steps and states abstract the information necessary to answer probabilistic spatio-temporal queries. The state transition system is fundamentally probabilistic as the biometric recognition that underlies events is inexact in nature. Our model supports multiple biometric modalities in a uniform manner and supports multimodal fusion. Unlike the HMM approach that is computationally more complex due to exponential nature of the state space, the state transition system approach is relatively simple with a quadratic state space. Additionally, in our approach, there is no requirement of learning a priori probabilities of trajectories as in HMM’s in order to determine the next state, as biometric recognition (or event) provides a direct means for effecting deterministic state transitions. Thus the state transition system model provides an effective abstraction of a smart environment and serves as an elegant basis for integrating various
recognition and reasoning capabilities and facilitates a precise statement of the performance aspects of a smart environment.

*Integrating Recognition and Reasoning:* Spatio-temporal reasoning techniques based upon an analysis of the occupant tracks helps determine the identity of a person more reliably rather than a single event. Our experimental results confirm the benefit of such an approach in minimizing the impact of recognition errors. Track analysis effectively simulates a higher order Markov process in that the state transition is based on multiple previous states rather than just the previous state. In this manner, spatio-temporal knowledge of the layout and adjacencies of the environment helps to eliminate the spurious occupant tracks, and fill the gaps in valid tracks thereby leading to improved valid tracks. Applying spatio-temporal reasoning helps to compensate for the shortcomings of a pure recognition approach and improves the overall performance of the smart environment.

*Precision and Recall Metrics:* We formulate precision and recall metrics in a query-independent and query-dependent manner in order to characterize the performance of a smart environment. Our definition of query-independent precision and recall refines the standard definition by incorporating a threshold thereby leading to bell-shaped precision curves instead of monotonically increasing or decreasing behavior. The intersection point of precision and recall indicates an optimal operating point at which the smart environment can maximize its overall precision and recall. The query-dependent approach evaluates the performance of the smart environment from an information retrieval perspective based on its responses to various probabilistic spatio-temporal queries.

*Probabilistic Spatio-temporal Queries:* The state transition system model provides a natural basis for answering diverse probabilistic spatio-temporal queries of varying complexity. The state transition system facilitates the formulation of data model based on the occupancy relation which captures the state information after recognition and reasoning have been performed and a set of valid occupants have been determined. The formulation of certain queries in SQL and CLP(R) involves computation of probabilities, an aspect that is novel to our model.
Simulator: The simulator realizes the state transition system model of a smart environment encompassing the three R’s: recognition, reasoning and retrieval and provides significant insights about the behavior of our model. The simulator helps us to understand the effect of scale (number of occupants), layout, quality of biometric sensors, and the role of declarative knowledge on the overall performance of a smart environment. The simulation results serve as a pointer for determining the choice of modalities of the biometric recognizers, the quality of the corresponding sensors, optimal recognition thresholds, and the type of reasoning needed in order to achieve a specified level of overall performance of the smart environment.

7.2 Directions for Future Work

Multimodal Fusion: In this dissertation, we have only utilized a single modality towards recognition - face. In an unconstrained smart environment, we can achieve better recognition by combining the output of two or more modalities, e.g., face, gait, or voice. The fusion methodology is transparent to our smart environment model since the fusion function returns a ranked list of occupants with the corresponding distance scores just as an individual recognizer does. The distance scores produced by multimodal fusion are converted to probability values using an approach similar to that described in reference [19]. Although our abstract model works uniformly for different biometric modalities, our experimental results have only utilized a single modality towards recognition - face.

Declarative Reasoning: We have investigated reasoning based on declarative knowledge of the environment such as layouts and adjacencies. It is possible to include declarative knowledge of the occupants based on their schedules (temporal knowledge) or learned behavior (spatio-temporal) to further enhance the spatio-temporal reasoning, which in turn can improve the overall recognition performance of the smart environment. We have investigated reasoning based on declarative knowledge of the environment such as layouts and adjacencies.
**Machine Learning:** Machine learning techniques such as Naive Bayes and SVM (Support Vector Machines) can be applied to the recognition output of the sensors over time to estimate the reliability of the recognition run associated with each sensor. The mean accuracy obtained by such techniques can determine the number of many times a recognition run ranked the correct choice as the top choice and the mean average precision indicates the how many choices the recognition system requires to generate to obtain the correct output.

**Query Processing and Speech Interface:** The probabilistic spatio temporal nature of the data generated in our model serves as an excellent example for further investigation into the domain of probabilistic databases. A variety of probabilistic spatio-temporal queries can be posed to the smart environment. Though we have explored only a cross-section of such queries, we can pose complex ‘what-if’ queries which cause the redefinition of one or more biometric events, thereby triggering the state transition module to compute a revised set of states. In keeping the spirit of a smart environment, we propose to develop a speech-based interface for posing natural language queries for information retrieval.

**Large indoor environments:** Our proposed research can be readily adapted to a wide range of scenarios, each differing in the extent to which the occupants in the environment are registered with their biometric templates stored in the enrollment database. In large indoor environments such as hotels and hospitals, a small percentage of the people entering the environment may not be pre-registered. In such cases, our approach can be extended to classify them as “unknown” and track them. In larger and more open-ended public environments such as shopping malls, airports and railway stations, the percentage of unregistered people is very large and therefore the focus shall be on monitoring specific zones, which is accessible only to a select group of registered people. Our approach can continue to track the unknown individuals through the monitored zones of the facility.