Simulation Modelling Practice and Theory 32 (2013) 99–115

Contents lists available at SciVerse ScienceDirect

Simulation Modelling Practice and Theory

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

Agent-based simulation of affordance-based human behaviors in emergency evacuation

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A R T I C L E   I N F O

Article history:
Received 20 May 2011
Received in revised form 30 November 2012
Accepted 6 December 2012
Available online 17 January 2013

Keywords:
Human behavior
Emergency evacuation
Affordance theory
Finite state automata
Agent-based simulation

A B S T R A C T

Complex cognitive processes corresponding to human control behaviors cannot be easily inferred using (1) a logical rule-based model, (2) a statistical model, or (3) an analytical predictive model. Predicting human behaviors in complex and uncertain environments like emergency evacuation is considered almost impossible (at least NP hard) in systems theory. In this paper, we explore simulating human behaviors using affordance-based finite state automata (FSA) modeling, based on the ecological concept of affordance theory. To this end, we introduce the conceptual and generic framework of affordance-based human behavior simulation developed through our previous work. Following the generic framework, formal simulation models of affordance-based human behaviors are developed, especially for emergency evacuation, to mimic perception-based dynamic human actions interacting with emergent environmental changes, such as fire. A "warehouse fire evacuation" case is used to demonstrate the applicability of the proposed framework. The human action planning algorithms in the simulation model are developed and implemented using the Adjusted Floor Field Indicators, which represent not only the evacuee's prior knowledge of the floor layout but the perceivable information about dynamic environmental changes. The results of our simulation study verify that the proposed framework accurately simulates human fire evacuation behavior. The proposed framework is expected to capture the natural manner in which humans behave in emergency evacuation and enhance the simulation fidelity of analyses and predictions of perceptual human behaviors/responses in the systems by incorporating cognitive intent into human behavior simulations.

1. Introduction

Recently, the need to observe, analyze, and predict human behaviors using computer simulation technologies has emerged in public and social system design, where humans and their inherent capabilities have eluded formal analysis. For example, in a terrorism-driven evacuation situation, a fire, or a natural disaster such as The station nightclub fire in 2003 [1] (the fourth deadliest nightclub fire in American history, killing around 100 people), understanding and predicting how a human will respond (or, more properly, how a crowd of humans will respond) within certain circumstances will allow

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http://dx.doi.org/10.1016/j.simpat.2012.12.007

law enforcement agencies to be better prepared and will greatly reduce the damage associated with these disasters. However, the cost of holding practical experiments is prohibitive, and the experimental data are difficult to capture [2].

Unlike traditional physical systems, from which humans are excluded, research on modeling and simulating human behaviors in human-environment complex systems has been slow due to the challenges associated with the nondeterministic and dynamic nature of the human action/decision making processes. The cognitive processes in human behaviors cannot be described simply using logical rule-based models, since predicting human behaviors under uncertainty is a highly complex systems problem [3].

While systems theory has grown rapidly, the modeling and simulation of human-environment systems that accommodate both human cognitive models and discrete system representations have not kept pace. This is especially true for discrete event-based systems, which comprise the best computational modeling methods of predicting physical system behaviors, as they can model event occurrences and changes of system states in either a deterministic or stochastic manner [4]. However, this is not so for human-environs, in which both discrete and continuous characteristics exist together, creating a major modeling void, given that most complex systems of interest to modern society are composed of human activities.

To overcome the challenge of addressing the human in systems, we start our discussion on the premise that perception guides a human's actions towards his or her goal. To this end, two related hypotheses regarding cognitive human actions are employed: (1) humans use perception-based actions in an ecological environment [5,6] and (2) humans utilize goal-directed actions through prospective control [7]. The former supposes that a human makes a decision to take an action based on the perceived information he or she takes from the environment. An ecological understanding of perception-based human actions in animal-environment systems was initiated by Gibson in 1979 [5]. He defines an affordance as "a property of the environment that provides an action opportunity offered to an animal (human), either for its good or ill." According to him, a human action is regarded as a consequence of direct perception of affordance and effectivity (an individual's ability to take a specific action). Thus, a human makes decisions to take action based on perceived information regarding sets of affordance–effectivity. On the other hand, the latter assumes that every human action has its own objectives or intentions for prospective control (i.e., the projection of control into the future); thus, every future human action can be interpreted as an intermediate goal to be realized to reach a final goal in the future, and a human makes a plan (a series of actions) to achieve the goal and anticipates the perceptually available outcomes and opportunities to take the series of actions that advance the plan.

From the viewpoint of systems theory, there are two kinds of approaches to modeling human behaviors: the experimental modeling approach and the formal modeling approach. The former method builds a model using an experimental monitoring of human behaviors through human-in-the-loop simulation [8]. This approach is seen as lacking in generality and completeness of experimental results due to its simplified and controlled laboratory conditions [14]. On the other hand, the latter is an attempt to represent the qualitative and dynamic nature of nondeterministic perception-based human behaviors using quantitative formal models. Kim et al. have advocated affordance-based descriptive formalism for modeling complex human-environment systems [9,10]. Formalism describes a system as a set of discrete states and regards the transitions between states as triggered by certain human actions leading to the next states in the computable models. In our previous conceptual investigation of the overall system architecture and generic functional components of an affordance-based simulator, we employed the modeling formalism of Kim et al. as the basis of our formal scheme [11].

The objective of this paper is to develop and verify an agent-based formal simulation framework of affordance-based human behaviors in emergency evacuation situations using formal modeling methods. We formalize perception-based human evacuation behaviors into a simulation model via the affordance-based FSA model, agent models, and a human action plan. Specifically, an algorithm of human behavior logic is presented. Using this algorithm, each human agent establishes and schedules a series of actions based on the dynamic perceptual properties of affordance and effectivity to reach the goal state. The proposed simulation framework is illustrated using a Warehouse Fire Evacuation (WFE) problem. The simulation results of a few different scenarios are studied to demonstrate the model's capacity to solve the considered problem.

When modeling and simulating human behaviors, other human attributes (such as emotions, cultures, knowledge levels, and social factors) need to be considered along with the perceptual properties. In particular, social factors such as interactions and communications within and between groups of people should be considered in human behavioral simulation models, especially in the case of an emergency evacuation [12,13]. In this research, however, our perspective on human behavior at this stage is limited to individual decision making with human perceptions rather than more complex problem domains involving human interactions and communication. Thus, only limited communication among human agents within their perceivable (or communicable) ranges is considered in the presented simulation framework. Other human attributes, such as crowd psychology and swarm intelligence, will be considered more specifically in the future. The framework and simulation models proposed in this paper will provide a predictive analysis capability for the design of human-involved systems, especially for emergency evacuation design and control.

The remainder of this paper is organized as follows: Section 2 provides the related work and background of this research. Section 3 reviews the overall system architecture of affordance-based human behavioral simulation. Section 4 presents a formal simulation framework of affordance-based human behaviors using the WFE problem. We demonstrate the applicability of the proposed framework and the capability of the simulation models by running a fire evacuation scenario in Section 5. Finally, we conclude this paper with a discussion of possible directions for future research in Section 6.