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A modelling formalism for human-machine cooperative systems

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This paper presents a collection of models of humans involved in complex systems with a focus on control of the system while allowing human participation in decisions for system operation. The existence of a formal model that captures human behaviour in a complex system allows for the efficient development of modelling and control software of man-machine systems. This paper provides a foundation for modelling and software development for complex systems that includes human activities. A modelling formalism, based on the automata theory for human-machine cooperative systems is demonstrated in this paper in consideration with the ecological concept of affordance.

Keywords: finite state automata; software development; affordances; human-machine systems

1. Introduction

This paper is submitted for the special session dedicated to the work of the late Dr Ezey M. Dar-El. Dr Dar-El was an industrial engineer who used tools related to production systems, human factors, tolerancing, and the engineering of complex systems. Interactions between Drs Dar-El and Wysk illuminated the need to consider the abilities of people in systems as a critical component for designing a system. 'You need to figure out what the people will feel comfortable doing in the system, mate. This should include both the physical work as well as the decision making that you expect from them.' Although I am sure that my recollections of his words are not quite as eloquent as those he actually used, he did consider people one of the most important parts of design. Hopefully, you will see some of his wisdom included in the models of this paper.

2. People in systems

While systems theory has grown rapidly, formalism for human-involved complex systems has not kept pace. We suspect that it is, in part, because no common framework exists to

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accommodate both human cognitive models and the discrete representations of control systems in which humans operate. This creates a major modelling void as most complex systems contain human activities. One fallout from the lack of integrated models is that the majority of software development time and code for these complex systems is spent to accommodate the human within the system in terms of human's non-deterministic behaviour, errors, and failures. The focus of this paper is to provide foundations for modelling and software development for complex systems, like manufacturing systems, that include human activities where a worker can participate naturally within the physical task performing and decision making for systems operation.

When a human operator acts as an autonomous system component, the complexity of human involved systems can appear seemingly unmanageable, because he or she can potentially access all other components within the system and perform an almost endless variety of activities, planned or otherwise. This is not the usual case of automated equipment whose behaviour is predetermined. Fortunately, in the time domain and the physical domain, the human has limitations/constraints that are based on limitations of both the human perceptual system and one's physical abilities. For example, a baseball player might observe a ball hit to the outfield and believe that by running to the required position, the ball then affords catching. He or she then puts into effect the act of moving to the position on the field to make the catch. As demonstrated in this simple example, the existence of a certain system affordance is limited by space and time (Gibson 1979). If the player begins the action within the proper time, the action potential of the player to catch the ball, by recognising the opportunity and utilising the proper physical constraints required to move to the proper position, produces goal-directed activities of catching the ball.

While catching a ball is a seemingly natural action that is practised thousands of times from childhood, it represents a fairly complex system and sequence of actions. The objective of catching the ball is often not realised (causing an error in baseball parlance), and when this occurs, significant replanning to retrieve and to put the ball into play follows. The human participation in the system produces two distinct forms of non-determinism: (a) executing the action of catching the ball; and (b) determining if the catch can be made. For systems that are exclusively operated by people, planning and replanning of actions occurs routinely. When the person is placed in an environment where he or she interacts with physical equipment (like a machine tool or packaging system), the equipment must be configured and controlled so that it can accommodate human participation. We believe that the development of formal combined environmental/behavioural models will enable the rapid development of software control systems for complex environs. In order to accomplish this activity, we combine concepts from cognitive and environment models. From the human activities viewpoint, affordances in the system have time-variant properties and space-variant properties. Therefore, what is desirable now may not be as desirable later and what is affordable here may not be there. So, we propose a modelling formalism of these dynamic affordances using an FSA modelling schema that can effectively accommodate the time and space-variant properties of affordance. We establish our formalism based on the hierarchical modelling concept which combines several basic models and defines the granularity of states in systems. Hierarchical FSA modelling can provide the structure for analysis of system complexities and a basis for the investigation of human planning activities.

3. Literature review

While FSA models are suited to model automated systems and some human activities, the vast majority of research on control models of human-involved manufacturing systems using FSA tends to consider a human as a system component that can perform tasks without any physical constraints (Shin *et al.* 2006a, 2006b). Therefore, representing human capabilities must be considered when modelling human-machine cooperative systems. It will enable the development of effective reusable controllers for human-involved complex systems and increase extensibility of complex systems software.

Under ideal conditions, human operators should be allowed to control all manipulable physical components in the system (Altuntas *et al.* 2007). In this sense, a human operator can be considered a distinctive component of the system that is capable of affecting both the logical and physical aspects of the system. In reality, however, the human can be restricted in affecting the system components given what is afforded (e.g., offered) by the task environment. To incorporate human capabilities into the system representation, one must consider the control opportunities offered to humans by the system environments as well as the judgment demands placed on human operators.

From the perspective of manufacturing system operations, most systems run with a goal to reach the system's desirable or pre-specified state. As a typical example, a shop floor is controlled in a manner that it produces a specific set of products. Each product goes through its own part states until it reaches a final state. A process planner uses the product requirements to determine what processing is necessary to convert a product from a certain state to a final one. At this time, the planner uses the environment to establish the set of possible processes that can be used to achieve a final part state (goal). In this sense, an affordance is quite similar to process planning in that it generates methods that can be used to attain a desired state.

In this research, a framework to develop a modelling formalism for affordance-based system representation for human-involved complex systems is proposed. The framework consists of two parts: (a) a set of formal models for a human-involved system based on FSA; and (b) a set of formal models for representing affordances in the systems. The major contribution of this research is to provide a framework to develop an affordance-based modelling formalism that can be used for highly complex and flexible systems with seamless scalability and granularity.

The term 'affordances' was first introduced by James Gibson in the following paragraph (Gibson 1979):

> 'The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment.' (p. 127)

More specifically, we define an affordance as a property of the environment taken with respect to an animal (human) and it provides an opportunity for an action by the animal, which has a property of effectivity, the capability to take the action (either for its good or for ill) within that environment to achieve a particular goal or objective. This opportunity for an action can also be viewed as a form of goal-directed control that is concerned with future events, also called prospective control (PC). Therefore, the environment offers a different set of affordances that may or may not be concurrently available to multiple animals that reside within this animal-environment system (AES).

4. Modelling a system with finite state automata

Our approach to capture human behaviour and participation within a complex system is to utilise Gibson's affordances within a finite state automaton (FSA) model structure. FSAs are a popular method to represent logical transactions of discrete systems based on the theories of languages and automata. This approach is based on the premise that any discrete event system can be modelled with discrete states and an associated event set (Cassandras and Lafortune 1999, Zeigler *et al*. 2000). An automaton, a formal modelling technique for discrete systems, is a mathematical model for a finite state machine (FSM). It consists of the finite number of states and transitions that prescribe system behaviour in terms of state changes via predetermined rules. These changes are described with transition functions. These transition functions determine which state to go to next, given the current state and a current input symbol. It is a kind of device that is capable of representing a language according to well-defined rules. The word, 'well-defined' means that it is rule-based and the state of the system is tractable (Sipser 2006).

The commonly used FSA in practice is the deterministic finite automaton (DFA), and it can be defined as a 5-tuple (Hopcroft 2001):

$$M = \langle \Sigma, Q, q_0, \delta, F \rangle,$$

where:

- Σ is the input alphabet (a finite non-empty set of symbols);
- Q is a finite, non-empty set of states;
- q_0 is an initial state such that $q_0 \in Q$;
- δ $\Sigma \times Q \rightarrow Q$ Q is the state transition function; and
- F is the set of final states such that $F \subseteq Q$.

As mentioned earlier, the terms affordance and effectivity are treated as a property of the environment and an animal's capability to actualise a potential action, respectively. In the formal representation of affordances, the environmental and animal components juxtapose to make a completely different property that belongs neither to the environment nor the animal (Turvey 1992). For example, a person (Z) can walk (q) stairs (X), can support something (p), and together they yield climbing (r) as shown in Figure 1.

This formal representation corresponds to the mathematical formalism such as FSA, as it provides the linkage between properties and discrete states, and the juxtaposition and state transition functions. If we consider the discrete states of the environment and the transitions between these states due to an animal's actions, then the entire

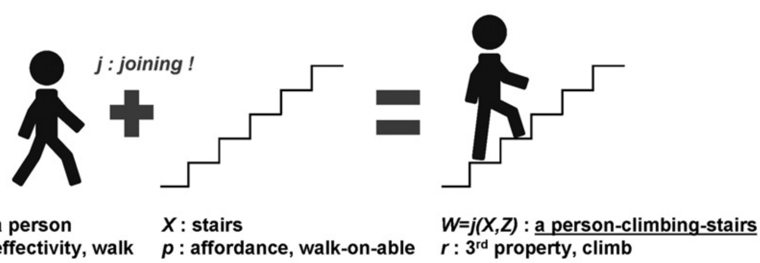

Figure 1. An example of a 'person-climbing-stairs' system (Thiruvengada *et al.* 2008). Reprinted with the permission of the Institute of Industrial Engineers, 3577 Parkway Lane, Suite 200, Norcross, GA 30092, 770-449-0461. Copyright © 2011.

animal-environment system (AES) can be expressed as a finite state automaton (Thiruvengada *et al*. 2008, Kim *et al*. 2009, 2010). The theory of automata corresponds to the ecological sense of affordances for at least the following two reasons: first, an environmental system can be described as a set of nodes and arcs that describe discrete states of the system and the transitions between states; second, an input to a transition function represents a component of the transition set, which is one of the potential properties (affordances) of the environmental system. There is a set of logically connected transitions from one state to another that corresponds to affordances of the environmental system and possesses a set of feasible transitions, which means dispositional properties in the system. The set of feasible transitions is triggered if and only if the input alphabet is included in the set of available actions in the environmental system. These input alphabets are considered effectivities. Then, it needs to be specified whether a human action can actually incur transitions in the general representation of FSA.

The use of this structure provides a powerful methodology that can be used to capture the essence of tools (resources) within a system and how people in the system can utilise the tools to accomplish specific activities.

Again, we address an FSA with a simple example of the person-climbing-stairs system shown in Figure 1. The representation of the 5-tuple FSA for the person-climbing-stairs system is shown in Figure 2(a). Transition from a lower level to an upper level occurs when a human takes the action of ‘climb stairs’.

However, this 5-tuple FSA model only represents the physical facts of systems behaviour, not the human aspects of availability and capability to accomplish a specific action (e.g., climb stairs). For this reason, to model human participation in the modelling purpose, it is essential to take into consideration the preconditions of human actions which consist of affordances (walk-on-ability) and effectivities (capability to walk) in the systems as shown in Figure 2(b).

In our model of a human-involved complex system, we adopt Turvey’s definitions of affordance, effectivity, property, attribute, and juxtaposition function, and add our

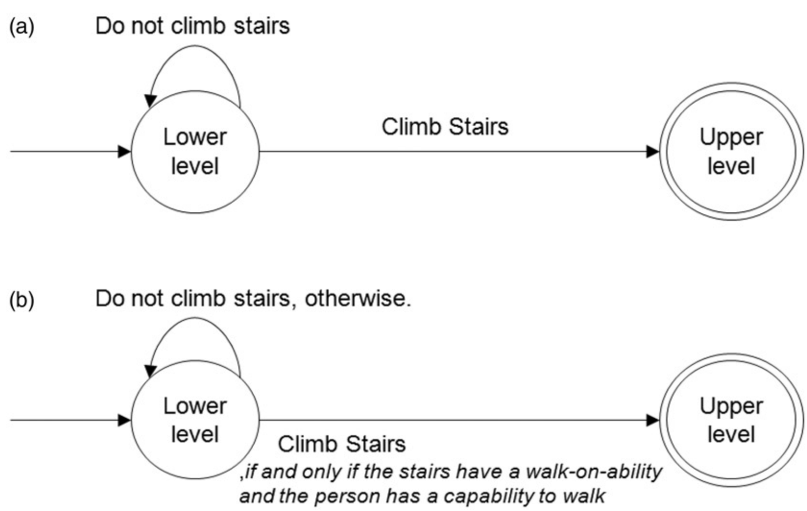

Figure 2. FSA representations of a ‘person-climbing-stairs’ system (Kim *et al*. 2009).

definitions on constraints, goals, and actions to formulate a finite state automata model. The class of behaviour which we are interested in modelling is referred to as visually guided actions because they are typically carried out under continuous control based on visual information. Fajen (2005, cited in Kim *et al.* (2009)) characterises the theories and models of visually guided actions as being shaped by three assumptions:

(1) The error-nulling assumption: observers make adjustments to null the difference between the current and ideal states by relying on information about the sufficiency of their current state.
(2) The single-optical-invariant assumption: observers rely on a single optical variable for each task that is invariant whenever the observer is in the ideal state.
(3) The keeping of the ideal state within the 'safe region' assumption: the observer's maximum action capabilities define critical boundaries separating possible actions from impossible ones.

As an example, consider the case of tracking a fly ball. While the ball-catching action is being performed, it is a continuous domain problem in virtually all respects (e.g., dynamics of the ball and kinesiology of the fielder). The action however results in either the successful completion of the affordance (catch the ball) or in an unsuccessful completion (fail to catch the ball). We propose that the outcome of the affordance can be discretised and modelled as an FSA.

5. Representation of affordance for prospective control

Prospective control means that human actions are taken based on specific goals (objectives) and they need to be predictable. In this context, we provide a more systematic definition of affordance and effectivity by providing a generic model of a human prospective control in Figure 3, based on Gibson's definition and Turvey's definition of affordance (Gibson 1979, Turvey 1992).

In this generic model, we define each term as follows (Kim *et al.* 2010):

- **Affordance** ($p_i \in P$)' is a dispositional property of the environment that offers an action opportunity for the animal, where X_p is the environmental system and p is the specific affordance type. It is an environmental precondition for taking an action within an environment and possesses a complimentary dual relationship with an animal capability known as effectivity. It is directly perceived by an animal.
  $P = \{p_1, p_2, \ldots, p_m\}$ = set of all affordances for the environment (X_p), where m is a positive integer.
- **Effectivity** ($q_i \in Q$)' is a capability of an animal that provides the propensity to bring about a possible action by actualising an affordance, where Z_q is the animal and q is the effectivity type. It is an animal's ability to take an action by actualising an affordance.
  $Q = \{q_1, q_2, \ldots, q_n\}$ = set of all effectivities for the animal (Z_q), where n is a positive integer.
- **Juxtaposition function** (j)' is a joining function that creates a manifested property (r that enables a specific possible action (pa)) that belongs to neither the environment (X) nor the animal (Z) but to the animal-environment system (W), which possesses the set of possible actions (PA).

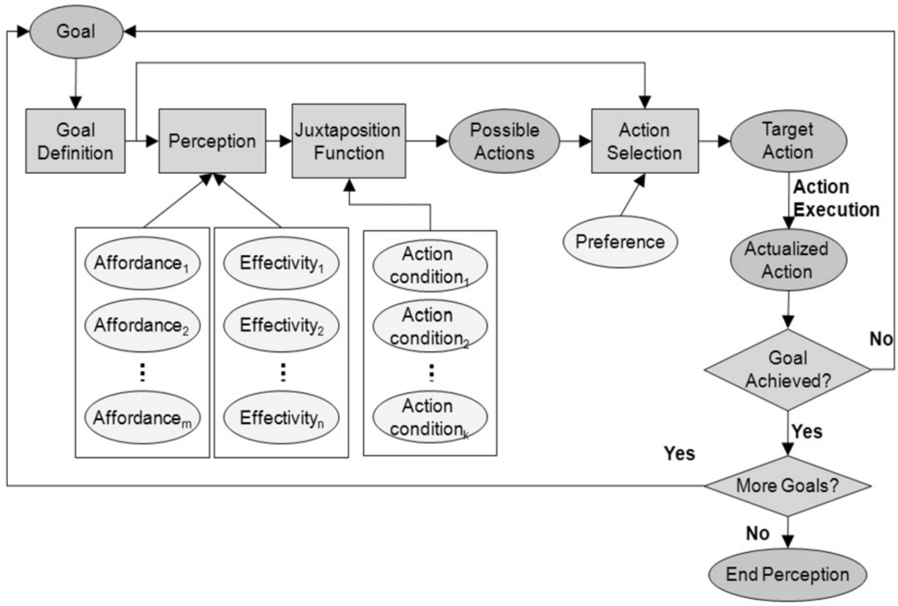

Figure 3. The generic model of human prospective control (Kim *et al.* 2010). Reprinted with permission (Kim *et al.* 2010, Modeling of affordances in human-involved complex systems using finite state automata (FSA). IEEE Transaction on Systems, Man, and Cybernetics – Part A: Systems and Humans. © 2010 IEEE).

- **Goal** or **sub-goal** ($g_i \in G$)' simply represents the animal's goals and the final desired or resting states for the animal. It directs perception of affordance (P) within an environment (X) by the animal (Z). It is a system state that finalises a specific action.
- **Action condition** ($c_k \in C$)' consists of a set of perceivable relational properties between the environment and the animal that filters affordance-effectivity duals into a set of possible actions. For example, the size of a ball should be less than the pocket size of a baseball grove which a field player wears, in order to catch the ball with the grove. An action condition specifies the relation between properties of the environment and the animal. The set of action conditions is denoted by $C = \{c_1, c_2, \ldots, c_k\}$, where k is a positive integer.
- **Possible action** ($pa_i \in PA$)' is an outcome of a juxtaposition function that results from a specific affordance-effectivity dual and its action conditions. It is a candidate of target actions that leads to a specific goal and is defined prior to the execution of actions. The set of possible actions is denoted by $PA = \{pa_1, pa_2, \ldots, pa_l\}$, where l is a positive integer.
- **Target action** ($ta \in PA$)' is the result of selecting an action from possible actions which are filtered by a specific goal and preference of the animal. The execution of a target action leads to a specific goal. A target action is denoted by ta.
- **Actualised action** ($aa \in PA$)' is the result of execution of a specific target action. The actualised action can make a transition between system states. An actualised

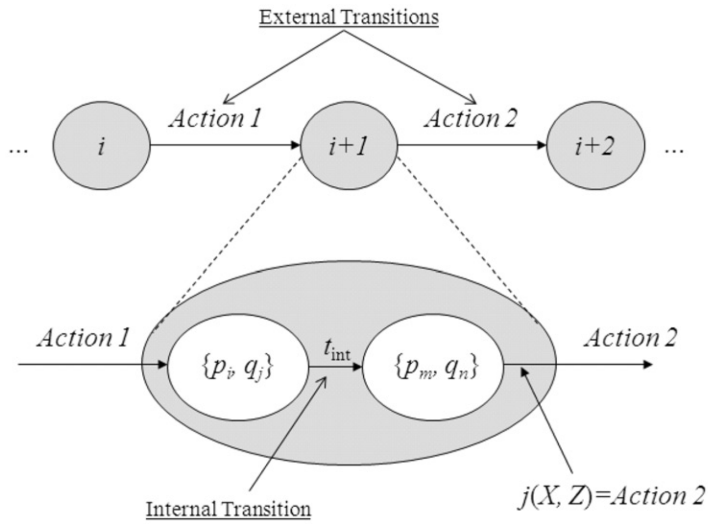

Figure 4. External and internal transitions in an affordance-FSA formalism (Kim *et al.* 2010). Reprinted with permission (Kim *et al.* 2010, Modeling of affordances in human-involved complex systems using finite state automata (FSA). IEEE Transaction on Systems, Man, and Cybernetics – Part A: Systems and Humans. © 2010 IEEE).

action is not always the same as a target action. It depends on the success rate of action execution which is a result of human expertness and the error rate. In the ideal system, we assume that the human is well-trained and well-motivated so that a target action always becomes an actualised action.

Turvey proposes that all things are said to have '**property**' (Turvey 1992). Neither properties nor individual things are really independent of one other. Affordances are real properties that imply the complementarity between an animal and its surroundings. A property may be either conceptual or substantive. For instance, a ball has 'size' property that allows one to conclude the volume occupied by the ball. P, Q, and R defined above are sets of properties. Function Pr incurs a set of objects' properties and their attributes. For instance, $\mathrm{Pr}: X_p \to P$. The above definitions in the generic model in Figure 3 are based on the Turvey's definitions, but they are much more specified in terms of their mathematical notation for the application of systems theory, especially the theory of automata. The generic mathematical representation of AES for a catching-a-ball example is developed in Section 6.

The graphic representation of internal and external transitions in the affordance formalism is shown in Figure 4. The internal transition connects two sub-states which are composed of a combination of a specific affordance and effectivities. These properties of affordances and effectivities are time-varying and determined by the physical limitations and human capabilities. In a certain amount of time, t_{int}, the status of affordances and effectivities are changed, and the juxtaposition function generates a set of 'possible human actions' based on the combination of p_m and q_n. If a possible human action is taken under specific action conditions, an external transition occurs and a physical state of the system goes to the next state.

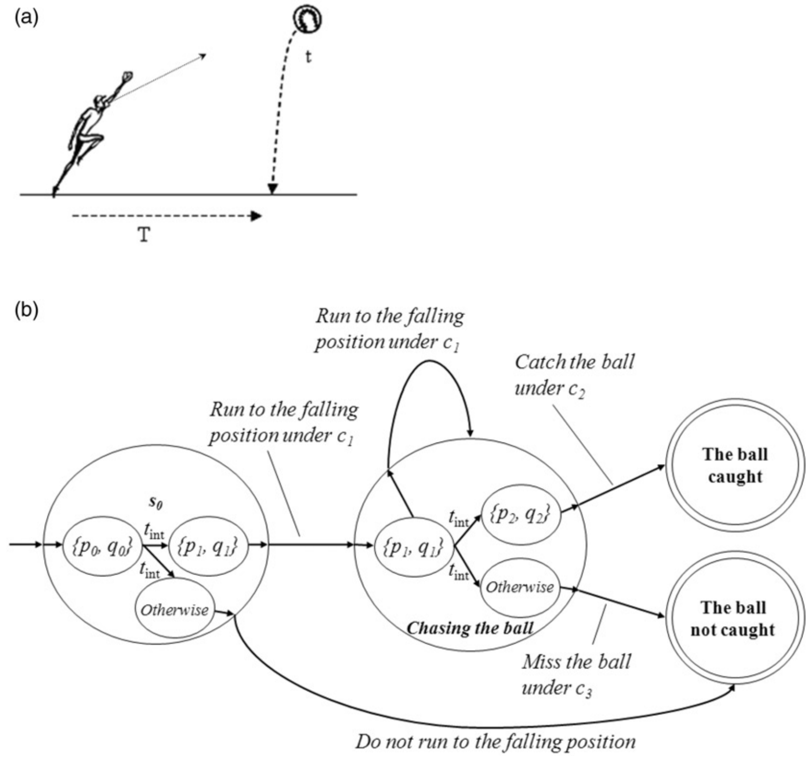

Figure 5. Fielder catching a ball (Kim *et al.* 2010). Reprinted with permission (Kim *et al.* 2010, Modeling of affordances in human-involved complex systems using finite state automata (FSA). IEEE Transaction on Systems, Man, and Cybernetics – Part A: Systems and Humans. © 2010 IEEE). (a) Fly-ball catching system: $t=$ time left until the fly fall reaches the ground; and $T=$ time left until the fielder reaches the falling position of the ball. (b) FSA representation.

6. Example: fly ball catching system

This paper aims at developing a computable model of affordances that can be validated. Hence, we will take an application domain in which optically-invariant variables are apparent and the safe regions of performance are perceptually available.

Consider a baseball example with a fielder trying to catch a ball (Figure 5). While the action is being performed, it is a continuous domain problem in virtually all respects (dynamics of the ball, kinesiology of the fielder, etc.). The action, however, results either in the successful completion (catching the ball) or in an unsuccessful completion (not catching the ball) of the affordance. Our perspective is that the outcome of the affordance can be discretised and possibly modelled as a finite state machine (Kim *et al.* 2010):

$$M^{\text{comp}} = \left\langle \Sigma, S, s_0 M^{\text{atom}}, \delta_{\text{ext}}, F \right\rangle, \text{ and}$$

$$M^{\text{atom}} = \left\langle \{X, Z, W\}, \{P, Q, PA\}, \text{Pr}, j, \pi, ta, \delta_{\text{int}}, t_{\text{int}} \right\rangle;$$

$$\delta : S \times \Sigma \rightarrow S,$$

$$\mathrm{Pr}: X_p \to P, \quad \mathrm{Pr}: Z_q \to Q, \quad \mathrm{Pr}: W_{pq} \to PA,$$

$$j: X_p \times Z_q \to W_{pq}, \quad \pi: P \times Q \times C \to PA, \text{ and}$$

$$\delta_{\mathrm{int}}: \{P, Q\} \times t_{\mathrm{int}} \to \{P, Q\},$$

where:

- Σ set of transitions among system states;
- S set of system states, $S = \{s_0$(initial), s_1(chasing the ball), s_2(the ball caught), s_3(the ball not caught)$\}$;
- F set of final states, $F = \{s_2$(the ball caught), s_3(the ball not caught)$\}$;
- j juxtaposition function;
- δ_{ext} system state (external) transition function;
- δ_{int} time advance (internal) transition function;
- Pr perceptual predicate function;
- π possible action generation function;
- X a fly-ball system;
- Z a field player;
- W a fly-ball-catch system;
- P $\{p_0 = \varphi$, $p_1 =$ field run-on-able, $p_2 =$ a ball grab-able with a glove$\}$;
- Q $\{q_0 = \varphi$, $q_1 =$ capability to run, $q_2 =$ capability to grab a ball$\}$, where φ means 'empty';
- C $\{c_1 : t \geq T$, $c_2 :$ pocket size of the glove $\geq$ size of the ball and the distance between the ball and the player is within his reachable range, $c_3 :$ either c_1 or c_2 is not satisfied$\}$;
- PA $\{$(run to the falling position, iff $t \geq T$), (catch the ball, iff size of the ball $\leq$ size of the glove and the distance between the ball and the player is within his reachable range), (not catch the ball, otherwise)$\}$;
- ta target action, $ta \in PA$ and $ta \in \Sigma$; and
- t_{int} time advance function.

7. Concluding remarks and summary

The formal model presented in this paper provides a methodology for mapping human activities on the finite state automata. More often than not, a human operator is not the same as machines because he or she can take an action after he or she has perceived, measured, and made a judgment in the system. For this reason, the affordance for a human operator in the system needs to be considered as an important factor for system representation. It can then contribute to the assessment of the human effects on the system.

To describe the system affordance for a human, a formal model of affordance is constructed and incorporated into this well-established model. Affordances are modelled as environmental preconditions for actions, and effectivities are treated as human capabilities under a given circumstance. As a result, the properties generated by a juxtaposition function can be mapped on a set of possible actions that can be made by a human.

We contend that the models illustrated in this paper can be used to create reusable and extensible software for control of complex systems. Thus far models have been developed for several environs to illustrate the concept for a variety of applications. Initial CASE tools have been created so that resources within models can be easily defined. We are in the process of developing a compiler that can be used to directly convert the formal model specification to software. We feel that this approach will enhance the use and reuse of components developed where people play a key role in system operations.

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