BDI Agent-based Human Decision-Making Model and its Implementation in Agent-in-the-loop, Human-in-the-loop, Hardware-in-the-loop, Distributed Simulation

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1) Research Objectives

The goal of this research is to develop a novel human decision-making agent (a piece of software) to replace the partial decision-making function of a human, whose role involves only decision-making functions as opposed to physical functions. The proposed agent is configured so that it asks for a human's input when it faces a situation that it cannot handled by itself. Otherwise, it operates autonomously. To this end, the detailed objectives are:

- To develop a human decision-making model (based on which the agent will be constructed), which is capable of 1) generating a *plan* (a sequence of actions required to achieve a goal) in real-time as opposed to selecting a plan based on a static algorithm and predefined/static plan templates that have been generated off-line, 2) supporting both the reactive as well as proactive decision-making, and 3) maintaining situation awareness in human language like logic to facilitate *real* human decision-making (in the case the agent cannot handle the situation). Importance of these features is discussed in more detail in Section 2.1.
- To develop a distributed computing platform, in which the agent, real human, and the environment (real or simulated) can be easily integrated to enable agent-in-the-loop, human-in-the-loop system (real system or simulated system). The proposed platform will be flexible, allowing us to test and demonstrate alternative agents, humans, and environments.

2) Summary on the Status of Research

2.1. Objective 1: Development of Human Decision-making Model

To achieve the first objective, we have employed BDI (belief, desire, intention) agent framework (Rao and Georgeff, 1998) to model human decision-making due to its solid philosophical foundation, and availability of formal logic and software supporting it. *Beliefs* correspond to information the agent has about the world. *Desires* represent state of affairs that the agent would wish to be brought about. *Intentions* represent desires that the agent has committed to achieve; therefore, an intention is a subset of a desire.

Task 1: In this work, we first have developed a new human decision-making model (see Figure 1) enhancing the traditional BDI framework. More specifically, the intention module in the traditional framework is expanded to include 1) deliberator sub-module, 2) planner (also called reasoning processor) sub-module, and 3) decision executor sub-module. Furthermore, an emotion state is also considered in the model, which affects as well as is affected by three other mental modules (belief module, desire module, and decision-making module). The proposed human model (see Figure 1) works according to the following steps. First, the agent (model) continually observes the environment to update its initial beliefs via the perceptual processor in the belief module. Second, based on the updated beliefs and initial intentions, the agent decides what states of affairs to achieve (desire) via the cognitive processor. Third, the agent then filters these desires and selects some of them (intention) to commit to via the deliberator. The agent then generates alternative plans via human like goal-oriented planning (planner) based on the current beliefs and guided by intentions. Finally, the agent selects an optimal/satisfactory plan based on decision-models and executes it via the decision executor.

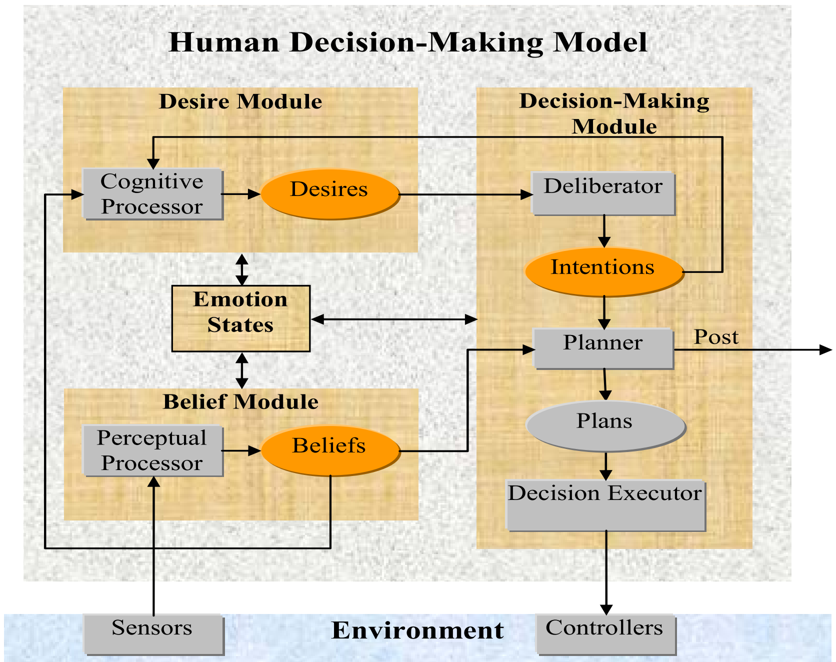

Figure 1. Proposed human decision-making model

Task 2: It is noted that beliefs, desires, intentions, and plans are specific to a role of human of particular interest. In this research, we have developed a human model in the context of the human operator who is responsible for error detection and recovery in a complex automated shop floor control system. To this end, the sub-functions required for error detection and recovery are formally mapped on to the beliefs, desires and intentions. In this work, we have employed LORA logic (Wooldrige, 2000) to represent beliefs, desires, intentions, and plans. We have picked LORA logic because of its rich expressiveness, combining first-order logic, temporal logic, and modal logic. Exemplary desires and intentions in LORA logic is shown in Table 1. The planner sub-module has been developed in a STRIP style. It is noted that we have developed a comprehensive beliefs, desires, intentions, and plans for error detection and recovery function in our work (Zhao and Son, 2005).

Table 1. Exemplary desires and intentions in LORA logic

	Scheduling level	Equipment level
Desires	$\Diamond\begin{pmatrix} part1(buffer3, m1) \\ \wedge part2(buffer4, m1) \end{pmatrix}$	$\Diamond(part1(buffer3, m1))$
Intentions	$\Diamond(part1(buffer3, m1))$	$\Diamond(part1(robot, \neg m1))$

Task 3: A scheme of integrating the proposed human agent with an automated shop floor control system (environment) has been developed. To demonstrate the proposed agent in an automated manufacturing system context, this work was essential. The contribution of this work to the field of automated shop floor control is significant, allowing seamless integration among the control system, an agent, and real-human.

Task 4: Another novelty of this work is to support both the proactive as well as reactive decision-making depending on the significance of the errors. The definitions of *proactive* and *reactive* here are different from those that are usually used in the field of reliability. Reactivity means the agent has perceptions of the world inside which it is acting and reacts to changes timely. Pro-activeness means that its behavior is not exclusively reactive but also driven by internal goals. In our work, the human decision-making model (see Figure 1) is configured so that catastrophic errors detected by the belief module result in reactive decision-making; other errors are handled by proactive decision-making (normal procedure described in Task 1 above).

Task 5: Finally, the human model (see Figure 1) has been implemented in JACK (state-of-the-art intelligent agent software). Furthermore, since JACK does not support real-time generation of a plan (it only supports static/predefined plans), we also have developed the planner sub-module in Java, which is callable from JACK software. Figure 2 depicts an instance of the real-time planning procedure, which is not explicitly explained here. The developed agent has been tested in a simulated environment (in Arena discrete event simulation package) using the distributed computing platform that we have developed (see below).

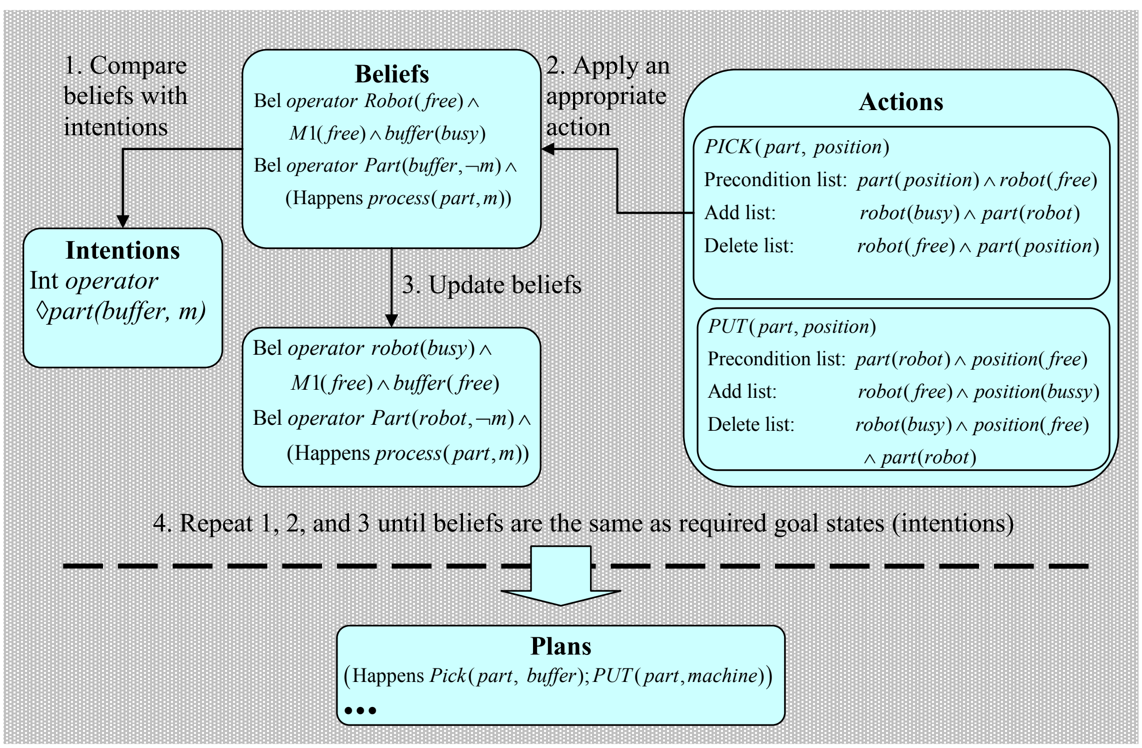

Figure 2. Real-time planning procedure

2.2. Objective 2: Development of Distributed Computing Platform

To achieve the second objective, we have developed a distributed computing platform based on DOD High Level Architecture (HLA) (now IEEE 1516 Standard) to facilitate integration of an agent (JACK software, Java application in charge of planner), real human, and the environment (real or simulated (Arena software)).

Task 1: Figure 3 illustrates the relationships between the components of the agent and real-human in-the-loop system. The agent can be implemented in different languages (e.g., JACK, AgentSpeak, Jadex, etc). The agent can interact with either a real environment (automated shop floor control system in our case) or a simulated environment. Also, the simulator (environment) can be implemented in different languages (e.g., Arena™, AutoMod™, ProModel™, etc). The direct interaction of the application software (both agent software as well as simulation software) with the RTI (executable component of HLA) is quite complex and cumbersome. Therefore, we have developed a Distributed Simulation (DS) Adapter, based on COM/DCOM technology, to provide mechanisms for distributed application similar to those provided by the HLA RTI, but with a level of complexity that is manageable by the development resources available in the non-computer science communities. The DS Adapter provides a simplified time management interface, automatic storage for local object instances, management of lists of remote object instances of interest, management and logging for interactions of interest, and simplified object and interaction filtering.

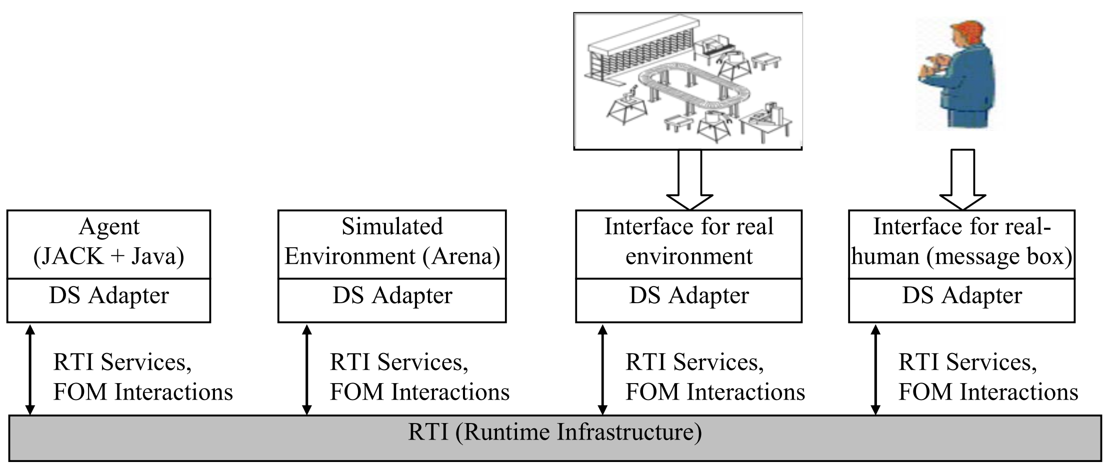

Figure 3: Integration of agent, human, and environment (real or simulated) based on HLA and DS Adapter

3) Accomplishments and New Findings

Contribution to the AI field: First, we have developed a human decision-making model, which is capable of 1) generating a *plan* (a sequence of actions required to achieve a goal) in real-time as opposed to selecting a plan based on a static algorithm and predefined/static plan templates that have been generated off-line, 2) supporting both the reactive as well as proactive decision-making, and 3) maintaining situation awareness in human language like logic to facilitate *real* human decision-making. Second, the proposed human decision-making model enhances the traditional BDI framework, expanding the intention module to include 1) deliberator sub-module, 2) planner sub-module, and 3) decision executor sub-module and considering an emotion state, which affects as well as is affected by the belief module, desire module, and decision-making module.

Contribution to the manufacturing field: To the best of our knowledge, the proposed model is the first human operator decision-making model in the manufacturing area capable of human like goal-oriented reasoning. Also, the contribution of this work to the field of automated shop floor control is significant, allowing seamless integration among the control system, an agent, and real-human.

Contribution to the distributed simulation field: The Distributed Simulation (DS) Adapter (based on COM/DCOM technology) that we have developed in this work provides mechanisms for distributed application similar to those provided by the HLA RTI, but with a level of complexity that is manageable by the development resources available in the non-computer science communities.

The proposed human decision-making model is targeted for a complex system, where a human must adaptively adjust his/her behavior to the dynamically changing environment. Although our work has been developed and demonstrated in the context of the error detection and recovery personnel in a complex automated manufacturing environment, it is expected that the model is directly applicable to the human operators dealing with complex systems in Air Force (e.g. pilots) and in civilian systems such as operators in a nuclear reactor, power plant, and extended manufacturing enterprise.

4) Publications

<Conference proceedings>

- Xiaobing Zhao, Jayendran Venkateswaran, and Young Jun Son, Modeling Human Operator Decision-Making in Manufacturing Systems Using BDI Agent paradigm, *in Proceedings of 2005 IIE annual conference*, May 16, Atlanta, Georgia, 2005 (6 pages).

<Journal papers>

- Xiaobing Zhao and Young Jun Son, Modeling Human Operator Decision-Making in Automated Manufacturing Systems Using BDI Agent Paradigm, *IEEE Transactions on Systems, Man, and Cybernetics*, (submitted in August 2005).

  This paper describes more details regarding our first objective (see Section 2.1).

- Jayendran Venkateswaran and Young Jun Son, Hybrid System Dynamic -- Discrete Event Simulation based Architecture for Hierarchical Production Planning, *International Journal of Production Research*., 43 (20), 2005, 4397-4429.

  This paper describes more details regarding our second objective (see Section 2.2).