AN EXPERT SURROGATE INSTRUCTOR FOR ACQUISITION OF COGNITIVE AND MOTOR SKILLS IN RIFLE MARKSMANSHIP

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Summary

This paper describes an expert system based interactive "surrogate instructor" for use in acquisition of perceptual training motor and cognitive skills related specifically to rifle marksmanship tasks. The objective of the surrogate instructor is to provide computer-based trainee task intervention just as human instructor provides when "looking over the shoulder" of the trainee. The instructional function will be provided by an expert program that will perform consistent diagnosis and individualized instruction while emulating either a specific instructor or an ideal human instructor. The system architecture is based on a real time blackboard model based on the "cooperating expert paradigm": These are (a) The Task Expert Model which makes up the standards of performance; (b) The Trainee model which tracks performance behavior and represents evolving trainee knowledge and skill; (c) Instructional model, which performs rule-based diagnosis of the trainee with respect to the expert model and generates instructional feedback; (d) A Curriculum Library which contains the instructional knowledge elements. The knowledge representation formalism central to the development of the expert model is the modified Petri Net (MPN). This model provides the procedural skills representation for training of psycho-motor skills. The (MPN) representation performs a two-fold function: (1) it provides the mechanism for robust representation of trainee behavior/performance for training diagnosis and (2) provides the basis for comparing a descriptive trainee behavior/performance model against an expert prescriptive performance model.

Background

The use of computers for education and training has been widely researched. The approaches that have been explored include drill-and-practice, programmed learning, and environments for experimental learning. The system discussed in this paper utilizes the computer as a surrogate instructor to provide a dynamic training environment. The system provides for task intervention just as human instructors provide it when "looking over the shoulder" of a trainee.

There are several reasons that a concept of surrogate training has drawn the interest of research sponsors. Training has become increasingly expensive, primarily because of rising personnel costs; there are too few qualified instructors to meet the increasingly high demand for instruction; and, because of varying instructor skills, the quality of training varies widely.

Automated surrogate instruction addresses these problems. It reduces the number of required instructors and allows each instructor to manage more trainees. With the aid of a surrogate instructor the human instructor is able to concentrate on providing detailed instruction to those students who exhibit exceptional difficulties with the task. Surrogate instruction may decrease training time for some students by providing each student with some aspects of the individualized attention that normally only a dedicated human instructor could provide. Surrogate instruction also provides adaptive, individualized training, and introduces an overall consistency in the style and content of training. This feature reduces the variance in post-training student performance. Surrogate instruction may also provide increased capability to diagnose the knowledge deficiencies responsible for trainee performance problems.

Definition of Surrogate Instruction

An automated surrogate instructor can be defined as an executable, knowledge-based model of either a specific or an ideal human instructor. Only such a model can provide the depth and flexibility of behavior that distinguishes surrogate instruction from other uses of computers for training. A surrogate instructor system consists of the following four major components:

(1) Expert Model. This is a representation of the knowledge underlying performance in the selected domain. Depending on the behaviors expected of the surrogate instructor, this representation can be either structural and static or procedural and dynamic (i.e., a running simulation of expert task performance).

(2) Trainee or Student Model. This is a representation of each trainee's knowledge of the selected domain and of other trainee characteristics relevant to differences in learning and performance. The system maintains a separate model for each trainee. Generally speaking, the representation of trainee knowledge is an "overlay" on the expert model or a variant of this model that can be generated by a set of transformation rules.

(3) Instructional Model. The instructional model has several major subcomponents. There is a diagnostic subsystem which, given observed values of trainee performance and the current trainee model, can update the trainee model. There is a syllabus that describes an initial plan and the order in which the knowledge in the expert model is generally best learned. There is a teaching subsystem that uses the student model, the syllabus, and the curriculum (see below). Given the student model for a specific trainee, the teaching subsystem can either predict (possibly non-deterministically) the effect on learning of alternative instructional

actions or can characterize the features of actions that would be beneficial to learning at that point. The teaching subsystem employs this capability to maintain a revised syllabus, or teaching plan, for each trainee.

(4) Curriculum Library and Generators. These are the elements within the training environments that the instructional model can control or select. Libraries are externally generated and are indexable by the knowledge underlying each element. Generators use a description of the knowledge underlying a desired element to produce an instance of such an element.

Together, as shown in Figure 1, the major components of a surrogate instructor interact to monitor and control a training environment by one or more devices, much as a human instructor does.

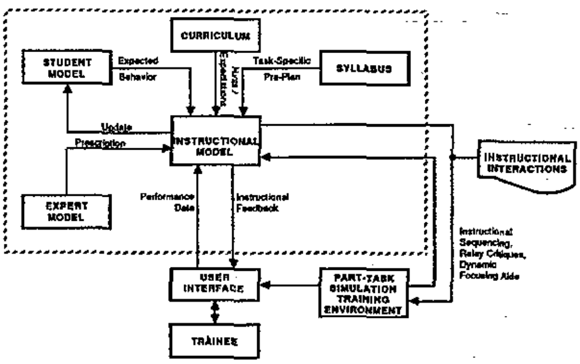

Figure 1. Surrogate Instructor System Concept

Prior Work on Surrogate Instruction for Training

Basic research on surrogate instruction for training has focused on learning in the context of task simulations or games. Briefly stated, the reasons for this are twofold: the motivational nature of computer-based interactive simulations and games, and the alternatives to verbal dialogs available for effecting learning. Dialog interfaces are neither competent nor motivating enough to serve as the primary medium in an interactive instructional system. In a simulation or game, the ability to teach via other direct actions within the task environment can provide more tractable and motivating interaction with the learner.

During the past 15 years, basic research has investigated surrogate instructor technique for computer-based training of a variety of skills. Individual projects have had different research foci, including:

- Diagnosis and representation of trainee skills and deficiencies.[1]
- Representation of task expertise for training purposes.[2]
- Modeling of student knowledge during training.[3]
- Design of pedagogically useful functional displays of the task environment.[4]
- Techniques for generating, selecting, and sequencing exercises for presentation to the student.[5]
- Methods for tutoring or "coaching" the student.[6]

This work has produced scientific knowledge and techniques capable of supporting applied development of surrogate instructional systems. For the most part, however, there have been no technology demonstrations of these capabilities in the contect of a complete instructional system for a military job function.

Furthermore, this work has been conducted solely in the context of tasks such as electronic troubleshooting, computer programming, medical diagnosis, or contrived games that have been considered exclusively from the standpoint of the intellectual skills underlying performance. No basic research in surrogate instructor technology has addressed training tasks with a significant perceptual motor skill component.

Expert Model

This expert model which is central to the successful development of a surrogate instructor is based on a new extension of the procedural skills representation, which has features needed to represent psychomotor skill.[7] A modified Petri Net (MPN) formalism is used to represent the control structure for the set or procedural skills underlying rifle marksmanship. The model was developed using a knowledge engineering approach with existing training materials and, where needed, human experts as resources.

A Petri Net is a type of procedural network in that it can represent knowledge structure. It enhances the capabilities of procedural networks to model information flow as well. The properties, concepts, and techniques of Petri Nets provide for natural, simple, and powerful methods for describing and analyzing the flow of information and control in systems, particularly systems that may exhibit asynchronous and concurrent activities. The major use of Petri nets has been the modeling of systems of events in which it is possible for some events to occur concurrently, but there are constraints on the occurrence, precedence, or frequency of these occurrences.

A Petri Net structure can be graphically represented by two types of nodes: circles (called places), and bars (called transitions). The nodes are connected by arrows (directed arcs) from places to transitions and from transitions to places. The nodes are arcs describe the static properties of a Petri net. The dynamic characteristics of Petri nets are represented by the movement of tokens (dots within places) according to some simple rules. Dynamic actions such as initiation of several concurrent activities and choice/decision making processes can be modelled by token execution patterns. Figures 2 and 3 illustrate the application of MPN's to modeling direct fire skills. Figure 2 represents the relationship among high-level skills exercises in engaging a single target. Figure 3 provides a lower-level decomposition of the the compute "sight picture" skill.

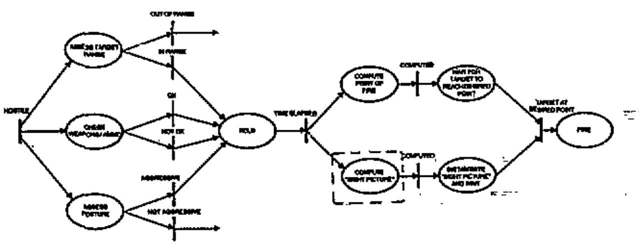

Figure 2. Partial MPN For Single Target Engagement

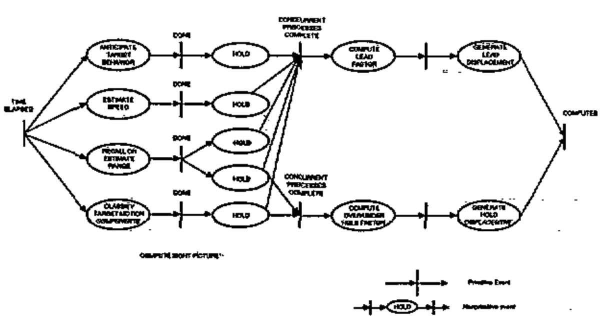

Figure 3. Compute Sight Picture

The Modified Petri Net formalism is advantageous for use in the expert model of a surrogate instructor for the same reason other types of procedural sets have proved useful. First, their modularity makes them transparent and easy to modify, useful characteristics if the model is to be used as a basis for student modeling. Second, they can be hierarchical, allowing skills to be represented at different levels of abstraction. This feature further enhances modularity. It also allows different skills to be represented as necessary, or possible, to different degrees of explicit detail, a feature we think is needed to represent psychomotor behavior. Flexibility of representation allows different types of skill components within the same model: perceptual and motor skills may have only a shallow hierarchy, with rather complex "leaves" on the network encoded only as "black box" procedures; on the other hand, cognitive decision making skills can usually have a deep hierarchy, whose nodes correspond to atomic, transparent rules.

A Modified Petri-Net model of task performance was developed specifically for M-16 rifle markmanship using a "knowledge engineering" methodology. This means that printed sources and interactions with and observations of expert marksmen were used to build a model of the "strategy" they use. This approach created the model from the top-down. At the same time, we built the model from the bottom-up by generalizing from findings in the basic literature on human performance. These included marksmanship exercises, low-level perceptual-motor processes, that are difficult or impossible for experts to describe meaningfully. The parameters and organization of processes at that level needed to be estimated and adjusted by simulation with the model.

Instructional Model

The interrelated components of the instructional model are the student model, the diagnostic subsystem, the syllabus, and the teaching subsystem. Our overall approach was to begin with relatively low-risk implementations of these components that were sufficient to support a demonstration of basic surrogate instructor capabilities. Then, depending upon available resources, some of the components of the instructor model were extended to enable more sophisticated system behavior.

Student Model

The initial method for representing student models was an overlay on the Petri-net representation of the expert model. The overlay assisted static annotations and the structural description of the expert model. It indicated a hypothesized state of learning for each process node in the network. The diagnostic subsystem determined state transitions from exercise performance data and trainee requests for lecture or demonstration involving specific behaviors. The overlay student model enabled the teaching subsystem to configure exercises dynamically for efficient learning and to support simple coaching behavior.

Another valuable technique for student modeling is known as a "procedural bugs" technique. This approach provides dynamic executable student models generated by substituting perturbed or "buggy" versions for parts of the Petri-net expert model. The Petri-net formalism provides a straightforward way to include perturbations that are misorderings, omissions, or substitutes of skill components. The perturbed versions are sufficiently detailed for the model to generate the deficits observed in a trainee's performance. The procedural bugs approach more clearly defines the nature of the knowledge/skill deficit, but about deficit form. However, the viability of the procedural bugs approach to student modeling and of explicit coaching is limited when there are multiple possible causes for performance deficits and no performance data available. Thus, the development of a surrogate instructor system for a task such as rifle marksmanship requires extensive expansion as well as integration of existing basic research products.

Psychomotor Skills in Marksmanship

Based on our initial analysis of the rifle marksmanship and of other direct-fire tasks (tank gunnery) we have worked with previously, we find it useful to identify seven categories of processes that bear on the structuring of the model: Detection, Discrimination, Motor Control, Tracking, Memory & Decision Making, Resource Management, and Metacognitive Contro. These categories are not orthogonal, but in groups roughly corresponding to different levels of abstraction in a conceptual hierarchy; the first three are at the lowest level, the next two at a higher level, and Resource Management and Metacognitive Control are at yet- higher levels. So, for example, Tracking can be viewed as a non-primitive process that integrates Discrimination and Motor Control processes. The overall organization of these seven categories of processes and other immediate abstractions that have no simple labels can be represented by a hierarchically structured extended Petri net. We will first describe each category in somewhat greater detail as it is reflected in the requirements of direct-fire tasks. Then, we will discuss why we find the Petri net formalism perspicuous for representing the organization of such categories of processes and present a small example based on a tank gunnery task.

Detection

The gunner must detect the presence of stimuli requiring his further attention. This is important only for field fire and moving target tasks. Detection requires skill at controlling eye scan of the field of view. When the shooter has fired at a target, he must detect the effects to determine if he has hit the target or if he needs to correct his aim point.

Discrimination

The gunner must perform a variety of types of discrimination and identification using visual data. Having observed a target, he must perform target identification to discriminate the target from the other candidates. This can influence th distance at which the shooter chooses to fire and the weapon fire mode. When the shooter fires, he must be able to discriminate the position of the target from the location of firing effects, and recognize the nature of the spatial discrepancy.

Motor Control

The gunner must manipulate his weapon to engage targets. This requires the fine control over the extent and timing of hand and eye movements, in conjunction with the visual processes used for Detection and Discrimination. Motor Control is integrated with these visual processes to define higher order processes like Tracking.

Memory/Decision Making

The gunner engages in several processes that require retrieval of information from memory, the application of rules to determine his behavior, and decision making when confronted with a variety of alternatives. For example, he must assess and select the most critical target to engage. This requires recall of engagement rules and situation assessment. He must decide which weapon mode to use against the target. This requires the recall and application of rules that map target identifications and threat evaluations onto weapon operation. He must recall the procedures for using the weapon and the aiming and firing heuristics appropriate for different target types. In particular, he must decide how much to lead a moving target. If the shot fails to hit the target, he must decide how to apply corrections for the next shot. Such target selection and weaponeering decisions may be knowledge-intensive in some direct fire tasks.

Tracking

Tracking skill is required to perform moving target acquisition. That is, the gunner must maneuver his weapon and hold aim on the moving target prior to firing. He must continue to track the target after firing so he can correct his position and fire again if necessary. The tracking operations must be performed smoothly and accurately to maintain an attack on the target. The tracking process includes a cognitive skill for generating expectations about target movements. Such expectations may be derived from knowledge of target capabilities, tactics, and environment (e.g., terrain).

Resource Management

The gunner must remain aware of the limitations on his available resources and manage their expenditure wisely. These resources include time needed to detect, discriminate, or track targets, alternative weapon modes, and amount of ordnance remaining.

Metacognative Control

In a time-stressed, dynamic task, the gunner may be exposed to a glut of incoming information that must receive rapid attention and action. Typically, there is insufficient time available to accomplish all the necessary tasks optimally. Therefore, a set of metacognitive control processes must monitor the needs of the various processes requiring the attention of the trainee. Control processes thus have several responsibilities. They must schedule the execution of various tasks and allocate cognitive resources to those tasks as called for by the changing situation. For example, following detection of a target, the control process should allow the discrimination process to execute, resulting in an identification of the target. The control processes must process interrupts from other processes or data as they are generated. Depending on the nature of these interrupts, the control process may alter the focus of attention to a new objective.

Intelligent Teaching Model

This planning and plan execution is the main function of the teaching model, one of the two major sub-models that comprise the instructional model. The teaching model determines the sequence, content, and method of presentation within each phase of the instructional model. A nominal ordering of content is suggested in the syllabus--a static database specified by human design. The syllabus is both a partial plan and a body of constraints. The actual ordering of content is varied dynamically for each trainee based on what the student model indicates about the trainee's state of mastery and on the instructional plan that has been executed thusfar. Both domain-specific and domain-independent rules within the teaching model operate on this information to revise and extend the plan for further instruction. There is a rich body of results from prior research that is utilized for the teaching model since there has been more success in developing domain-independent techniques for instructional planning than for other functions.

Various forms of coaching are implemented. On a shot-by-shot basis, verbal cues can be given during the shot to shape behavior. For example, airing cues such as "left...left...steady...fire" could be generated using the testbed capabilities. Cues for breath control, "inhale...exhale...hold... fire" could similarly be generated. On a "string" basis, coaching is integrated with performance assessment by presenting "canned" material which suggest corrective behavior changes based on the teaching model's analysis of the student model.

While performance feedback is presented in some node continually, one important aspect of the teaching model is deciding when coaching is appropriate. Previous work has addressed this issue and developed heuristic rules for coaching. Factors addressed by these rules include making advice salient, not interfering with performance, and not alienating by "overcoaching."[8] In addition to these, there is need to consider the ambiguity of the student model with respect to the cause of performance deficits. The teaching model does not initiate coaching of specific behaviors unless the student model provides an unambiguous diagnosis that those behaviors are the cause of observed deficits. Where there is significant ambiguity, the teaching model can rely on implicit methods of behavior shaping by manipulating exercise parameters to focus on specific knowledge and skills and thereby enhance opportunities for trainee self-kcorrection while avoiding actions that might invalidate the surrogate instructor in the trainee's eyes.

Ambiguity of Model-Based Diagnosis.

Diagnosis is the interpretation of performance data as hypotheses about student mastery of knowledge and skill. The diagnostic model is the second major sub-model of the instructional model, generating the student models that constitute one of the major inputs of the teaching model. Diagnosis is generally the most difficult capability to implement in a surrogateinstructor. The main problem is that there are sometimes alternatives, employing different subsets of knowledge and skill, for achieving correct performance in a task. Also, there are usually alternative hypotheses about knowledge and skill mastery that are consistent with observed performance deficits. Therefore, it is usually necessary to converge on a hypothesis using performance data from different problems that exercise different combinations of knowledge and skill. The WEST[9] and WUSOR[10] systems are good examples of this approach. However, when the options for configuring problems to exercise different skills is limited or the performance data that could discriminate hypotheses are not available, then diagnosis cannot be unambiguous. When this is the case, critique and direct instruction are limited because of a need to prevent the learner from believing that the surrogate instructor has incorrectly decided that they have not learned some particular knowledge or skill; instead, indirect methods of promoting learning, such as manipulation of exercise parameters, are preferable because ambiguous hypotheses about the trainee are only implicit in these methods.

Curriculum Library & Generators

The curriculum can be made up of either off-line versions of existing training tests or on-line versions adapted for display on the computer's display. On-line text and illustrations are best for two main reasons. First, on-line presentation is easier to integrate physically, eliminating the need for the trainee to manipulate printed materials while positioned to fire the M-16 simulator. Second, by organizing the material into an indexed database, it can also be used in the delivery of selective reviews based on performance evaluation. It is also desirable to provide dynamic, realistic illustrations using interactive videodiscs. An advantage of employing videodisc for lecturing is that it reduces the extent to which the system's effectivenexx depends on reading skill.

Additional demonstrations relevant to other components of marksmanship can be presented using high-resolution graphics. This method is effective for components for which there are overriding visual cues that can be emphasized in schematic form, where there are no natural visual illustrations, or where there are time-phased relationships that can be illustrated by synthetic displays. Examples of such components are sight picture--especially for moving targets--, breath control, and the interaction between breath and trigger squeeze dynamics. The graphic demonstrations can either be "canned" or generated using an expert performance model for the task. The latter is most useful for demonstrating performance components that vary across a continuous situational parameter, e.g., sight picture for targets moving at different speeds at different ranges under different wind conditions.

Practice exercises on zeroing, known distance, and pop-up target tasks of the curriculum, as well as the moving target tasks, will be presented to the trainee. For initial training, syllabus design will favor scheduling initial lecture, demonstration, and practice of these different tasks listed. However, the surrogate instructor can control the parameters and duration of exercise involving the different tasks to achieve criterial performance in a cost-effective manner. The model will be able to exert the most control in the pop-up and moving target, tasks where there are more complex parametric variations possible and correspondingly complex skill requirements. For other parametric variations, most importantly wind effects, that exercise more skills, the system should operate so that the different task types are repeated in dynamically varying sequences depending on trainee performance.

Conclusion

Marksmanship training is an expensive, instructor intensive, time-consuming and geographically-restrictive task. The cost and availability of ammunition and its storage and transport to rifle ranges are logistic problems for depots, logistic support units, and using/requisitioning units. However, a more important problem is instructor availability and quality.

Primary marksmanship instructors are of varying quality and usually assigned multiple trainees. Continuous supervision and "looking over the shoulder" of each trainee is not physically possible; hence, instructor strategies and behavior often appear inconsistent to the trainee. The perceived inconsistency, whether real or imagined, can adversely affect trainee performance. The ideal training environment would provide a one-to-one instructor-student ratio, where the problem difficulty would be selected according to the student's skill level. Performance would be immediately assessed, remedial actions applied, and session actions critiqued.

The use of artificial intelligence (AI) techniques in intelligent computer-assisted instruction (ICAI) appear to offer a solution to the identified instructor-student training problems. However, while basic research in surrogate instruction techniques have produced scientific knowledge and identified techniques capable of supporting applied developments over the past ten years, there have been no technology demonstrations of these capabilities in the context of a complete instructional system with a military job function. What has been demonstrated has been conducted solely in the context of tasks such as electronic troubleshooting, computer programming and medical diagnosis, which exclusively consider the intellectual skills underlying performance. No basic research in surrogate instructor technology has addressed training tasks with significant perceptual motor skill component. This task will require extension as well as integration of existing basic research knowledge and products.

This paper describes a concept for the artificial intelligence techniques in ICAI systems in military training simulators. The paper covers a generalizable architecture for the expert surrogate instructor. The system extends and integrates techniques and approaches successfully demonstrated in prior basic research investigations of ICAI.

This paper describes:

(1) An expert performance model of M-16 rifle marksmanship incorporating memory, decision making, and motor components.

(2) A student model that describes the trainee's evolving skills and deficiencies with respect to the expert model.

(3) A diagnostic procedure that maps low-level task performance data onto skill and deficiency descriptions in the student model.

(4) A teaching procedure that can plan and deliver appropriate sequences of "lecture" material, demonstration, of problem exercises, and feedback and coaching on exercise performance in order to optimize skill acquisition and remediation.

The concept described here contributes to the state-of-the-art in both military training and applied cognitive science. In military training, the concept demonstrates a capability for computer-based surrogate instruction for tasks that are currently difficult and expensive to train in real-world settings. In addition, it makes several contributions to the technology base of cognitive science and instructional theory. The concept produces an expert model architecture for a class of tasks which include sensory, motor, and cognitive components. In addition, it addresses important instructional issues such as the dynamic, model-based sequencing of learning situations and the integration of instructional interventions into dynamic, simulator-based practice.

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