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## Final Report for LDRD Project 11-0783: Directed Robots for Increased Military Manpower Effectiveness

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# Final Report for LDRD Project 11-0783: Directed Robots for Increased Military Manpower Effectiveness

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## Abstract

The purpose of this LDRD is to develop technology allowing warfighters to provide high-level commands to their unmanned assets, freeing them to command a group of them or

commit the bulk of their attention elsewhere. To this end, a brain-emulating cognition and control architecture (BECCA) was developed, incorporating novel and uniquely capable feature creation and reinforcement learning algorithms. BECCA was demonstrated on both a mobile manipulator platform and on a seven degree of freedom serial link robot arm.

# 1 Introduction

Existing military ground robots are almost universally teleoperated and occupy the complete attention of an operator. They may remove a soldier from harm's way, but they do not necessarily reduce manpower requirements. Current research efforts to solve the problem of autonomous operation in an unstructured, dynamic environment fall short of the desired performance. In order to increase the effectiveness of unmanned vehicle (UV) operators, we proposed to develop robots that can be "directed" rather than remote-controlled. They are instructed and trained by human operators, rather than driven. The technical approach is modeled closely on psychological and neuroscientific models of human learning. Two Sandia-developed models are utilized in this effort: the Sandia Cognitive Framework (SCF), a cognitive psychology-based model of human processes, and BECCA, a psychophysical-based model of learning, motor control, and conceptualization. Together, these models span the functional space from perceptuo-motor abilities, to high-level motivational and attentional processes.

## 2 Problem Statement

There continues to be a trend in all branches of the military toward doing more with fewer people. The proliferation of unmanned aerial, ground, and underwater vehicles attests to this, as do stated goals for increased manpower effectiveness in major programs such as Future Combat Systems (FCS). Fully automated unmanned vehicles (UVs) are appealing, since they require no attention during operation. However, full automation has not yet become practical for most systems, particularly for ground vehicles operating in unmodeled environments. Instead, current designs require almost constant supervision from at least one operator.

In order to increase the effectiveness of UV operators, we propose to develop robots that can be "directed" rather than remote-controlled. They will be instructed and trained by human operators, rather than driven. Over time, as they learn appropriate behaviors and world models, directed robots will increase in autonomy and require less supervision. This approach is analogous to how a human apprentice is trained-not through controlling his actions, but through repeated instruction, demonstration, and feedback.

Existing military ground robots are almost universally teleoperated and occupy the complete attention of an operator. They may remove a soldier from harm's way, but they do not necessarily reduce manpower requirements. Current research efforts to solve the problem of autonomous operation in an unstructured, dynamic environment fall short of the desired performance. The teams in DARPA's Grand and Urban Challenges that have shared their approaches reveal that the algorithms used rely heavily on knowledge of the environments and obstacles that they will be facing, even if the specific configuration and timing of these must be discovered real-time. The types of failures observed in some teams reveal these limitations in spectacular fashion. The same is true of Honda's ASIMO, the autonomous

vehicles of CMU's NAVLAB, and the robotic follower demonstrated by TARDEC.

The weakness of most existing approaches lies in the dual facts that they do exactly as they're told, and they're told exactly what to do. In any given situation, either the programmer's heuristics or the teleoperator's commands specify every action that the robot should take. They do not learn from their experiences, improve their performance with practice, or form increasingly sophisticated representations of their environments and tasks. The proposed BECCA-SCREAM architecture is designed to do these things, potentially giving it the capability to perceive and perform far beyond the ability of any heuristic-based system. Partial exceptions exist, such as the neural-like approaches of the MIT Humanoid Robotics Lab and Steven Levinson's lab at the University of Illinois, as well as some Programming by Demonstration systems. These learn by interacting with their environment or observing an operator, but they lack the ability to form new symbolic representations based on their experience.

### 3 Project Goals

The goals of the project have been centered around technology demonstrations in the belief that these would 1) focus technological development more rapidly than abstract goals and 2) make a more compelling illustration of the progress achieved to potential funding sources.

The goals for the three-year period covering the fiscal years 2009-2011 are as follows:

Goal	Milestone	Completion Date
Typed command-directed behavior		
	Basic principles demonstration	04/30/2009
	Full demonstration	08/30/2009
Structured speech-directed behavior		
	Basic principles demonstration	04/30/2010
	Full demonstration	08/30/2010
Simple natural speech-directed behavior		
	Basic principles demonstration	04/30/2011
	Full demonstration	08/30/2011
Documentation		
	Communicate Results (Annual)	09/23/2009, 2010, 2011
	Final SAND Report	09/23/2011

### 4 Technical Accomplishments

The demonstrations were documented and described in a series of journal and conference papers and video segments. The set of demonstrations proposed as project goals were achieved with one exception. In year three, the goal of directing a task with natural speech commands

was modified to be directing a task 1) with human training feedback 2) on multiple robotic platforms. This change was made to accommodate an increased benefit to be gained from demonstrating the generality of the approach, rather than making a single implementation more sophisticated.

The accomplishments are described in detail in the referenced publications. Links to all can be found at [www.sandia.gov/rohrer](http://www.sandia.gov/rohrer) . Here is a brief description of each.

- B Rohrer, “**A unified architecture for cognition and motor control based on neuroanatomy, psychophysical experiments, and cognitive behaviors,**” Brain-Inspired Cognitive Architectures Symposium, AAAI Fall Symposium Series, Washington, DC, Nov 7-9, 2008.

This conference paper is a description of BECCA with an earlier version of the feature creator and reinforcement learning (RL) algorithms. The feature creator algorithm BECCA used at the time was Context-Based Similarity (CBS) and the RL algorithm was S-Learning.

- B Rohrer, “**Robust performance of autonomous robots in unstructured environments,**” American Nuclear Society Winter Meeting, Reno, Nevada, Nov 9-13, 2008.

This conference paper is a description of S-Learning applied to simulated 2 degree of freedom (dof) and 7 dof robot learning tasks.

- B Rohrer, “**S-learning: A model-free, case-based algorithm for robot learning and control,**” 8th Intl Conf on Case-Based Reasoning, Seattle, Washington, July 20-23, 2009.

This conference paper is a description of S-Learning applied to a simulated light-seeking mobile robot navigation task.

- B Rohrer, M Bernard, JD Morrow, F Rothganger, P Xavier, “**Model-free learning and control in a mobile robot,**” 5th Intl Conf on Natural Computation, Tianjin, China, Aug 14-16, 2009.

This conference paper is a description of S-Learning applied to a Surveyor SRV-1 mobile robot. An accompanying video at [www.sandia.gov/rohrer/videos.html](http://www.sandia.gov/rohrer/videos.html) shows a demonstration of the learning behavior reported in the paper.

- B Rohrer, JD Morrow, F Rothganger, PG Xavier, “**Concepts from data,**” Brain-Inspired Cognitive Architectures Symposium, AAAI Fall Symposium Series, Washington DC, Nov 5-7, 2009.

This conference paper describes CBS and another feature creation algorithm that was based on state space partitioning, kx-trees.

- B Rohrer, “**What we might look for in an AGI benchmark,**” 3rd Conference on Artificial General Intelligence, Lugano, Switzerland, Mar 5-8, 2010.

This conference paper presents a set of criteria for selecting performance measures and long-term research goals for the problem of Natural World Interaction, the general formation of the problem that this LDRD is attempting to solve.

- B Rohrer, “**Accelerating progress in Artificial General Intelligence: Choosing a benchmark for natural world interaction,**” *Journal of Artificial General Intelligence*, 2:1-28, 2010.

This journal paper extends the previous conference paper, proposing a benchmark for Natural World Interaction, the Search and Retrieve task.

- B Rohrer, “**Concept acquisition for dialog agents,**” *International Journal of Computational Linguistics Research*, 1(3):189-201, 2010.

This journal paper was based on a talk I was invited to give at AISB, the British artificial intelligence society. It covers feature creation through both CBS and kx-trees.

- B Rohrer, “**kx-trees: An unsupervised learning method for use in developmental agents,**” 9th International Conference on Development and Learning, Ann Arbor, Michigan, Aug 18-21, 2010.

This conference paper describes kx-trees and presents the results of applying them to several small problems.

- B Rohrer, JD Morrow, P Xavier, F Rothganger, “**BECCA: A BICA for arbitrary robots in unknown worlds,**” 1st International Conference on Biologically Inspired Cognitive Architectures, Washington, DC, Nov 12-14, 2010.

This conference paper describes BECCA with kx-trees as the feature creator and S-Learning as the RL algorithm.

- B Rohrer, JD Morrow, F Rothganger, P Xavier, “**BECCA: A functional model of the human brain for arbitrary task learning,**” [poster] Second Workshop on Grand Challenges in Neural Computation, Santa Fe, NM, Feb 21-24, 2011.

This conference paper describes BECCA with a feature creator and RL algorithm in nearly their current form. BECCA is demonstrated performing on a 1-dof visual servoing task.

- B Rohrer, “**An implemented architecture for feature creation and general reinforcement learning,**” Workshop on Self-Programming in AGI Systems, Fourth International Conference on Artificial General Intelligence, Mountain View, CA, Aug 3-6, 2011.

This conference paper describes BECCA with a feature creator and RL algorithm in nearly their current form. BECCA is demonstrated performing on a 1-dof visual servoing task. At this conference, BECCA was also demonstrated driving two CoroWare Corobots in simple learning tasks.



- B Rohrer, “**A developmental agent for learning features, environment models, and general robotics tasks,**” Joint IEEE International Conference on Development and Learning and on Epigenetic Robotics, Frankfurt, Germany, Aug 24-27, 2011.

This conference paper describes BECCA with a feature creator and RL algorithm in nearly their current form. BECCA is demonstrated performing on a 2-dof visual servoing task. BECCA’s feature creator demonstrated the creation of a hierarchical set of visual features during the course of the task.

- B Rohrer, “**Biologically inspired feature creation for multi-sensory perception,**” Second International Conference on Biologically Inspired Cognitive Architectures, Washington, DC, Nov 5-6, 2011.

This conference paper describes BECCA’s feature creator creating hierarchical sets of both audio and visual features.

- N Malone, R Lumia, B Rohrer, L Tapia, J Wood, “**A general reinforcement learning algorithm implemented on a 7 degree of freedom serial link manipulator,**” [submitted] International Conference on Robotics and Automation, St. Paul, MN, May 14-18, 2012.

This conference paper describes BECCA’s performance on a Barrett WAM manipulator learning simple navigation tasks and demonstrating manual training.

- B Rohrer, “**BECCA code base**” [www.sandia.gov/rohrer/code.html](http://www.sandia.gov/rohrer/code.html) , last updated July 29, 2011.

This collection of MATLAB scripts provides all the code for the most recent version of BECCA and the published demonstrations.

Taken collectively, these publications provide a comprehensive catalog of the progress made in this LDRD.

## 5 Programmatic Accomplishments

### 5.1 Academic Reputation

The consistent engagement with the academic community that the LDRD enabled allowed Brandon Rohrer to establish relationships with key individuals in two closely related and partially overlapping communities: artificial general intelligence (AGI) and biologically inspired cognitive architectures (BICA). As a result, Brandon has served on the core organizing committees for both conferences, is an associate editor for the journals of both AGI and BICA, and is a founding member of the BICA Society. Aside from the rich source of intellectual inspiration that these activities provide, prominence in these communities translates into a willingness of academic colleagues to partner in seeking external funding, more positive reviews of submitted papers and proposals, and an increased likelihood of obtaining external

funding. The relationships spawned by this increase in academic standing are in their early stages still, but have already resulted in many discussions of potential collaboration.

## 5.2 Partnerships

One partnership with the academic community that has materialized is with the robotics and manufacturing laboratory at the University of New Mexico. In the third year of this LDRD, Nick Malone, PhD Candidate, integrated BECCA with the WAM in UNM robotics lab. Nick is a student of Prof. John Wood (Mechanical Engineering) and also works closely with Prof. Lydia Tapia (Computer Science) and Prof. Ron Lumia (Mechanical Engineering. Profs. Wood, Lumia, and Tapia have invited Brandon to partner with them in responding to the National Robotics Initiative call. Brandon is the team member responsible for robot learning, the key technology advance represented in the proposal. (Nick has also invited Brandon, who has a joint appointment with UNM's Electrical and Computer Engineering Department, to participate on his doctoral committee.)

The partnership with UNM is ideal and may become a model for future partnerships. The capabilities of the parties are complimentary. UNM has exceptional robotics facilities, including two WAMs on a track, but no in-house robot learning expertise. This arrangement leads to a natural combining of hardware and software skills on collaborative projects.

# Acknowledgment

I gratefully acknowledge the contribution of many minds and hands in this three year effort.

Pate Brogger and Sean Hendrix, undergraduate students at Oklahoma State University, endured a summer internship integrating BECCA with CoroBots and developing tasks for the CoroBots to perform. In a bold live demonstration, they showed their work at the 2011 AGI conference and received a lot of positive attention in a field dominated by simulations and toy problems.

Nick Malone worked through the third year of the project to integrate BECCA with a WAM. Coming from a computer science background, he got quickly and intimately acquainted with the suffering involved with hardware integration. With a great deal of perseverance, he completed the integration and developed several tasks, resulting in the most compelling hardware demonstrations BECCA has been a part of so far.

Profs. John Wood, Ron Lumia, Rafael Fierro, and Lydia Tapia all lent their insights, support, expertise, and enthusiasm to the project at various times and in various measures. Without their support it would have had no foothold outside of Sandia.

As other team members became committed to their own projects at the end, Sandia programmers Rudy Sandoval and Ben Lawry stepped in to help carry the torch across the finish line.

John Wagner has provided consistent behind-the-scenes support for the project, which has been very helpful. The periodic high-level conversations about the work we have had has also helped to clarify in my mind its position relative to other work and business interests at Sandia.

As always, the ultra competent administrative support provided by Stephanie Willis contributed to the project moving forward in many ways which were noticed and appreciated and many more, I'm certain, that escaped notice altogether.

In addition to the technical work performed, attributed in the individual papers listed above, a small group of Sandians provided a forum for tumbling and polishing the conceptual bases for BECCA. Mike Bernard, Dan Morrow, Fred Rothganger, and Patrick Xavier helped provide context and help BECCA avoid the dangers of being developed in a vacuum. I hope to rely on them for this service in the future.

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