HETEROGENEOUS AGENT OPERATIONS IN JWARS

A WHITE PAPER

PREPARED BY:

PAUL BROSS
AND
JOHN PRINCE
AND
HARVEY JOHNSON
AND
H. RIC BLACKSTEN

CACI INC - FEDERAL
1100 NORTH GLEBE ROAD
ARLINGTON, VA 22201

http://www.caci.com/

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Chuck Burdick
Lockheed Martin Corp.
1555 Wilson Boulevard
Suite 620
Arlington, VA
22209
703-696-9490
chuck.burdick@lmco.com

Harvey Graf
The Mitre
Corporation
7515 Colshire Dr.
McLean, VA 22102
703-696-9490
hgraf@mitre.com

James Huynh
Mihaly Grell
Don MacQueen
AT&T GSI
1900 Gallows Road
Vienna, VA 22182
703-506-5000
dmacqueen@grci.com

LTC Harry Argo, USA
JWARS Program
Office
1555 Wilson Blvd,
Suite 620
Arlington, VA 22209
703-696-9490
harry.argo@osd.mil

Paul Bross
John Prince
Harvey Johnson
H. Ric Blacksten
CACI Inc. – Federal
1600 Wilson Blvd Ste 1300
Arlington, VA 22209
703-875-3030
rblacksten@caci.com

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ABSTRACT: This paper reports on work done by the JWARS office to create autonomous, heterogeneous agents for the purposes of better differentiating unit behaviors at the lower echelons of JWARS. The agents represent a wide range of military units and use a knowledge base of facts, rules, and associated actions to reason about their own situation, the enemy situation, and the environment. With a relatively small set of rules that can be tailored by side, by country, by type of unit, and by skill level, units of differing capabilities, functions, and perceptions produce a rich set of unit behaviors and provide more realistic military operations and interactions without human intervention. The approach offers opportunities for the development of sets of doctrinal and procedural behaviors that are observable and modifiable by the user community.

1. INTRODUCTION

One of the most difficult parts of building an analytical simulation is generating credible unit behavior while not exceeding mandated maximum run times. Realistic behavior has to factor in many variables and consider large numbers of options in a two or larger sided conflict, and this consumes run time. Conversely, high speed execution demands tight coding methods and this often keeps the user from easily making changes in doctrine or other factors that modify unit behavior.

The JWARS Land Warfare team and the JWARS C4ISR team have collaborated to apply some of the Knowledge Base (KB) processes associated with higher level decision making to this problem in the Joint Warfare System (JWARS). An approach has been developed that assists the user in building rule sets and associated inputs to give the user a great deal of control over unit behaviors. This paper describes the objects that exhibit behavior in JWARS, the factors in JWARS that effect and affect that behavior, and the actions taken to make them more agent-like while still meeting the required representation of land warfare. It describes how JWARS is attempting to provide a rich initial set of behaviors and enabling users to modify these behaviors and create new sets of behaviors.

Figure 1 shows the general structure of a JWARS Battle Space Entity (BSE), the primary object for all JWARS behavior.

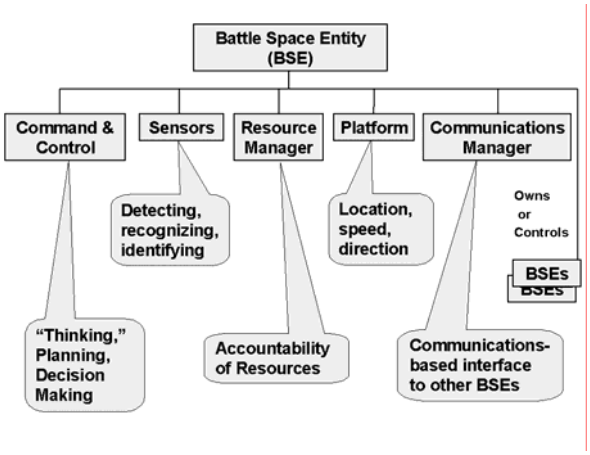

Figure 1. A High Level Representation of the JWARS Battle Space Entity (BSE)

For JWARS land forces, agents are configured as military units and civilian groups. These units are not decomposable, but can temporarily spawn subordinate units for specific tasks, if the need arises. Thus, for the remainder of this paper, the term "unit" will be used rather than agent. The focus of JWARS land unit decision making is generally on robustness (do something appropriate) versus optimality (do the best there is), but the behavior model offers both as options for individual leader characterization as well as a hybrid strategy. Generally it is assumed that it is unlikely that a true optimal course of action can be found in the time available and without complete

information. But even more important, the optimal solutions tend to be optimal only within a very small set of conditions, most of which can change quickly.

Previous efforts in JWARS behavioral development addressed the representation of soft factors such as training and morale and the development of a Commander's Behavior Model (CBM) (1,2). Those efforts allowed the JWARS user to create units with different capability level and different leadership patterns in terms of a Commander's willingness to risk his own troops, his desire to destroy enemy forces, his concern with maintaining his supplies, and his commitment to accomplishing his mission. These few parameters, in various combinations, have generated a wide range of behaviors reflected in the plans produced by the Commanders assigned to higher level organizations such as Army Divisions and Corps. Supplementing these representations of leaders are several KBs consisting of collections of facts, rules, and subsequent actions. In past JWARS releases, these KBs have been assigned only to high level units to support their assessment of the situation and subsequent behavior.

1.1 Overview of the JWARS Approach

The JWARS objective is to bring enough situation assessment capability to lower level units to provide them with credible autonomous operations within the constraints of orders and formations dictated by higher headquarters. From the unit's point of view, its assessment becomes more situation dependent. Furthermore, the implementation method of KBs allows users to easily change doctrine in broad classes of units (by country, by type of unit, etc.). This paper describes the JWARS efforts to create KBs applicable to tactical forces (lowest level units) and examines the options, difficulties, and advantages of implementing the concept in a military hierarchy.

2. BUILDING AGENTS IN JWARS

2.1. KB Development at the Unit Level

To create units that react appropriately to their situation, JWARS has provided a set of tools that modify the way in which units interpret their situation and react. Since units in JWARS differ in many ways, the user is offered the opportunity to modify behaviors and tie the actions taken to specific unit attributes including unit function, type of unit, training level, and morale.

2.2 Equipping Units with Knowledge Bases

JWARS has already provided KBs to high level decision makers within the JWARS land hierarchy, including the Joint Force Commander, the Joint Force Land Component Commander (JFLCC), and multiple Corps Commanders. KBs by their nature are "plug and play" modules and can be applied to any unit, but the high level facts, rules and associated actions are not very applicable to tactical forces. For these units, the emphasis is on the development of facts, rules, and actions associated with tactical Doctrine and Tactics, Techniques, and Procedures (TTP) rather than on theater level decisions.

Graphical User Interfaces have been provided so that the JWARS user can build KBs and assign them either to individual units or groups of units. Figure 2 shows this interface. Every individual unit KB will be the product of appropriate facts, rules, and actions.

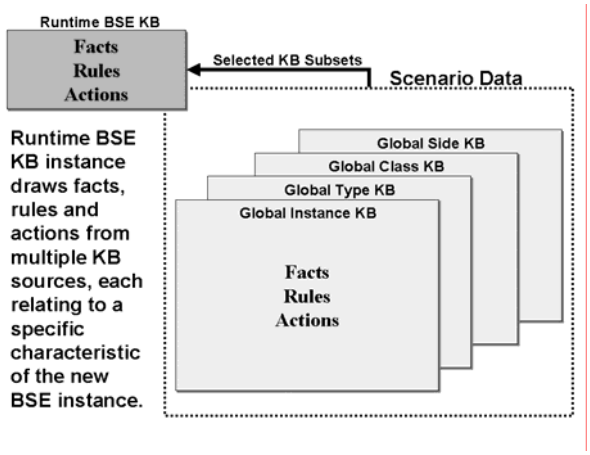

Figure 2 KBs for New Units are Built from Multiple Sources Appropriate for the Particular Unit

Even when the rules in the KBs are identical, their instance values (numerical, Boolean, or text strings) will reflect the situation of the particular unit doing the assessing. Identical units with identical KBs can hold very different perceptions since the facts on which their rules are based are often perceptually biased and may be wrong or out of date.

2.3 Facts

Facts constitute the basic information that can be reasoned about. As a fact is updated, an automatic KB process is triggered based on defined relationships (fact dependencies) captured through rules. Forward and backward chaining are executed as the associated rules fire to determine what, if any, resulting change has occurred, and whether any action is required. Facts can be "primitive" or "derived." The values of primitive facts come directly from the simulated environment. As shown in Figure 3, primitive facts of interest to the low level KBs are related to the unit, its local situation, and its local environment. These facts can be simple Boolean true or false statements, integer or floating

point values, or strings of text with meanings defined in the Smalltalk code.

Unit Attributes	
Coalition/Side	Nationality
Function: Cbt, CS, or CSS	Echelon: Bn, Brigade
Type: Armor, Mech, Inf	Is a Headquarters?
Role: Left Flank, Reserve	Rank or Skill Level
Unit Situation	
Unit is under fire	Days in combat
Unit is in contact	# of enemy in contact
Unit Current Strength	Formation/Orientation
Unit Current Objective	Local Activity/Mission
Units is On/Off Plan	Has specific asset
Global Conditions	
Is Day/Night	Weapons free/tight
Chemical Use Authorized	Unit is in Country X
Vegetation type	Terrain type
Weather	Civilians are present

Figure 3. Primitive Knowledge Base Facts

The values for derived facts are determined based on the value of other facts (primitive and / or derived) and the relationship of those facts to one another as reflected in associated rules. Primitive facts must have some basis in the JWARS code, usually as attributes of friendly or enemy units or of the environment. Shown in Figure 4 are derived facts that might be reasoned from simpler primitive facts about the type of units involved and the environment.

Primitive Facts	Related Derived Facts
Resources	
# of Personnel	Skill Levels
Type of Equipment	Condition/Strength
Amount of Supplies	Expected Resupply
Knowledge of Capabilities	
Ability to Sense	Enemy Situation
Communications	Intercept Potential
Own Operations	Available Options
Enemy Operations	Enemy Intentions
Own Doctrine	Expected Enemy Reaction
Environment	
Weather (current)	Favorable for unit
Weather (forecast)	Favorable for unit
Terrain	Favorable for unit

Figure 4. Reasoning from Available Facts

Derived facts may only have applicability to the units triggering them. Thus while the actions to be taken by two units on favorable terrain might be identical, terrain that is perceived as favorable for an armor unit may or may not be favorable for an infantry unit or even for a less capable armor unit. The facts do not have to be limited to specific states. Thus, fuzzy hedges may be employed to create facts such as somewhat favorable or very favorable. It is believed that other behavioral work can be easily integrated into this approach. This is particularly applicable to reuse of work by the JSIMS Land Component Team, which developed behavioral rules that included methods for computing intangibles such as the perceived "strength" of a defensive position. Similarly, work by Army TRAC on the effect of surprise on unit effectiveness in the AWARS models can also be of benefit to JWARS.

2.4 Rules

While many facts must have pre-existing code in the current JWARS release, JWARS rules, which are stored as data, generate Smalltalk code during model initialization, and thus do not need to be in the source code. The user can employ the Rule Builder GUI shown in Figure 5 to insert an unlimited number of new rules. Since rules can be stored externally as data, it is believed that it will be easy to swap sets of doctrinal rules without modifying any JWARS code.

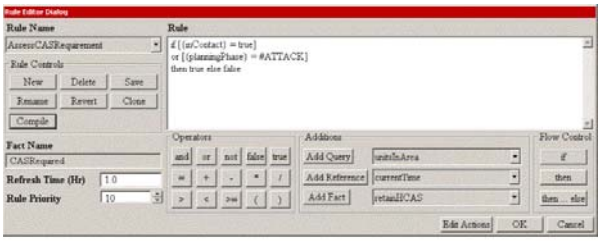

Figure 5. JWARS Rule Builder User Interface

The simplest JWARS rules employ very basic logical relationships (*greater than*, *and*, *or*, etc.), while the more complex ones reason about whether the situation is favorable or unfavorable for a particular unit (*if*, *then*, *else*). Thus the JWARS user can build a wide variety of new rules as long as the rules only reference existing (previously coded) primitive facts or facts that can be derived from them. JWARS Land units use both standard and fuzzy logic rule sets. However, in the upcoming release, only the standard rule set is modifiable by the user. This restriction will be removed in future releases as automated help and intuitive graphical interfaces are added to assist the user in using fuzzy rules.

2.5 Actions

Once rules fire, there must be some associated effects. At a minimum, rules determine whether derived facts change values. While changing derived facts is useful, JWARS is primarily concerned with generating sets of general actions that can be executed when certain conditions are true. Thus, we may want a unit to perform an action such as move when an enemy is

considered close (where *close* is relative to the locally perceived situation and the size and type of units involved) and how far the unit is to move is likewise dependent on the situation. Or, when some other rule fires, we may want an action to be taken such as ordering a subordinate to conduct a specific task or requesting a service from some supporting unit.

3. JWARS AGENT OPERATIONS

The earliest and simplest JWARS agents were unit objects whose actions were determined by a perceived global state and a set of rules (*when State S is true, then the Agent X should take action A*). In the evolving JWARS approach, emphasis is being put on units recognizing situations unique to themselves and their local conditions. To do this, they use current and prior knowledge of self, the environment, enemy, neutrals, and command guidance, which includes constraints on actions. When a situation is perceived by a particular unit, then the agent will select among a set of available/allowable actions it perceives as appropriate. This selection is based on its expectation of finding an outcome that meets its objectives (though is not necessarily optimal). If no feasible solution can be found or the risk is perceived as too great, then the problem is "bucked up the chain" to a higher headquarters to resolve, while the unit "soldiers on" until some local breakpoint is reached.

This paper focuses on JWARS efforts to assign sets of these KBs to lower level units both to increase their breadth of behavior and to allow the user to customize agent behavior by mixing and matching facts, rules, and actions appropriate to the unit and its potential situations. Since these low level units exist in many types and functions, the KBs must generate a rich set of behaviors in many different situations. Since the low level units come in many varieties with differing assets and capabilities, they are referred to in this paper as heterogeneous agents to differentiate them from homogeneous agents where all agents have the same capabilities and use similar or identical rule sets. Some readers may argue the applicability of the term, but the following discussion describes the reasoning power available to these agents and the ability of users to easily give them a varied collection of rules supporting behaviors appropriate to the situations they may encounter.

3.1 Unit Creation

JWARS land units are created with a wide range of assets, perceptions, missions, and capabilities. Assets can include weapons, sensors, personnel, equipment, and supplies necessary to accomplish a wide range of tasks. Perceptions are a function of unit context, sensor capability, memory, standard operating procedures, the assessment of the current situation, and projections from current assessments. Thus a unit facing a "strong" enemy force computes "strong" only in comparison to itself or its force and not some arbitrary strength figure. For example, a unit that is at full strength with artillery support should see the situation differently than one with significant losses and no fire support.

Unit missions or goals can be combat or non-combat related and will eventually encompass all military missions and certain relevant civilian operations. Capabilities are special skills that are only limited by the needs of the simulation. These range from relatively simple tasks such as loading supplies on vehicles and mine clearing to complex tasks such as maneuver planning.

Units can be created (initialized) with fewer or more assets than authorized, with sets of capabilities to support its desired set of behaviors, with different skill levels for those capabilities, and with a set of standard operating procedures similar to, but not necessarily identical to its peers. Once initialized, the unit is given general guidance appropriate to its side and the current state of the scenario, a specific mission (which could include doing nothing beyond maintaining itself), and access to its side's common intelligence picture.

Even when doing "nothing," a JWARS unit is never completely static. The unit must consume supplies to maintain itself and, consequently, is regularly seeking to replenish those supplies, which involves communications of some type. In addition, the environment is regularly changing. For example, as the time of year advances, the number of hours of daylight changes. The variation in the hours of darkness may in turn impact on the unit capabilities to move, sense, shoot, transfer supplies, etc. and the unit must be aware of this and factor it into its assessments.

In a C4ISR-driven model, the physical state of the agent and its world often do not match its perceived state. JWARS agents regularly change their status by one or more of the following mechanisms:

- By messages from other agents, such as
  - Orders,
  - Under Fire Messages
  - Logistics and Fire Support Requests, and
  - Sensor Reports
- By direct interaction with other agents or the environment
  - A senses B
  - B shoots at and destroys some of A assets
  - C delivers new assets
  - D moves more slowly at night

- By internal operations
  - Consumption, fatigue, repair
- By changes in perceptions of self, the enemy, and the environment as new information is sensed

Thus the information on which it is operating can be misperceived for a number of reasons ranging from poor sensors to enemy deception. Dealing with conflicting information and uncertainty (lack of information in comparison to nominal conditions) is currently very limited at lower echelons. JWARS generally deals with conflicts with the premise that unless A is specifically forbidden, then it is allowed, but not required. However, even if an action is specifically forbidden, situations may occur where incorrect information causes a unit to violate a constraint such as limiting collateral damage as when an enemy unit is located with undetected civilians. In other cases, units may violate orders when they reach physical or mental breakpoints (withdrawing or cowering while other units are still attacking). JWARS explicitly models such unit breakpoints (both temporary and permanent) due to losses or perception of force ratio. JWARS does not currently play mistakes by agents. Enough "bad" things already occur due to lack of current, accurate, and/or complete information in a perception based environment.

JWARS units have multiple capabilities and can perform multiple actions or tasks concurrently, assuming they are not simultaneously impossible such as staying and fleeing. Thus the action of consumption is automatically associated with shooting and moving, and sensing is generally continuous during all other activities. JWARS Land units are not tied to specific global states, although they do recognize the overall Phase of the Campaign. Thus, the degree of an agent's action may be modified by the perception of the relative presence of the elements of the situation and their weighting. For example, when encountering a large enemy force, a unit with incomplete information on the location of other friendly forces may withdraw, until the situation is better clarified. The more uncertain the situation, the earlier and faster the withdrawal. Once the situation is clarified, then additional, more appropriate, actions may be taken. In any case, the unit calls for indirect fire support, notifies its superior of the contact, and takes what protective measures it can.

JWARS does not relax obligations/missions when they cannot be satisfied. If a unit is told to attack, it continues to employ every resource it can access to achieve the mission, while not violating constraints such as number of friendly losses. Actions to achieve the plan can include requesting higher priorities for resources, employing more resources by actions such as committing reserve forces, and by applying additional fire support against the force opposing the unit. All of this can be influenced by the unit's KB. However, once failure is perceived as likely by a unit (by looking ahead) or actually occurs (unit breakpoints are reached), the unit abandons the mission. Higher headquarters can reverse those decisions, but cannot enforce them unless it changes a factor in the subordinate's assessment of the situation. Thus the offer of air support would increase the unit's perceived strength even though this may not translate into actual destruction of enemy units.

3.2 Use of Knowledge Bases in JWARS

As described in Burdick et al (2)., JWARS used KBs at higher echelons in its 2002 release. In its upcoming July 2003 release, JWARS is expanding the use of KBs to its lowest level units while not violating the constraint that these units continue to operate under the orders of their higher headquarters. Initial applications include small unit decisions to commit to or withdraw from battle. Unit withdrawal decisions are currently represented by temporary breakpoints determined by equipment and personnel losses per time period (depending on echelon) and permanent breakpoints figured in terms of total losses. However, it is apparent from the literature that casualties and equipment losses are not the primary cause of unit failure to reach their objective. For example, McQuie (3) evaluated 80 battles in World War II and the Arab-Israeli Wars. As shown in Figure 6, only ten percent of battle failures were credited primarily to unit casualties.

REASON for WITHDRAWAL	%
Maneuver	
Envelopment, Encirclement, Penetration	**33**
Adjacent Friendly Unit Withdrew	**13**
Enemy Occupied Key Terrain	**06**
Enemy Achieved Surprise	**08**
Enemy Reinforced	**04**
Enemy Firepower	
Casualties or Equipment Losses	**10**
Heavy Artillery and Air Attacks	**02**
Other Reasons	
No Reserves Left	**12**
Supply Shortage	**02**
Truce or Surrender	**06**
Change in Weather	**02**
Orders to Withdraw	**02**
TOTAL	**100**

Figure 6. Reasons for Withdrawing from Battle

Thus most causes for withdrawal were either situationally or environmentally based, requiring more complex reasoning beyond the simple assessments of unit losses, supply shortages, or orders to withdraw. Furthermore, many of these complex reasons often occur in combination, making the assessment more complex. At the same time, they are often ameliorated by the condition of the unit doing the assessment. For example, units with high morale or with an excellent defensive position and lots of supplies would likely hold on longer. It is believed that rule sets in the JWARS unit KBs can make such assessments using an increasingly rich set of criteria. As JWARS matures and more rules are built, the units should be able to assess increasingly more complex situations.

Without the KB, there have been instances at the lower echelons in JWARS when combat units that should have engaged one another have missed that opportunity by simply returning fire and continuing on to their objective. Circumstances have also occurred where units without KBs have inappropriately engaged in combat. For example, in some situations a logistics support unit may inappropriately assess the situation and close with an enemy infantry battalion. The KB supports the desired outcome by improving the ability to assess the situation and subsequently altering individual unit courses of action. As shown in Figure 7, attacking combat units sense enemy fire, close with the enemy units, and, after destroying them or forcing them to withdraw, resume their original mission. Meanwhile, support units with both the friendly and enemy sides assess the local situation as dangerous and attempt to keep clear of the direct fire battle. Their ability to still provide their side with support is dependent on their assessment of the danger to themselves.

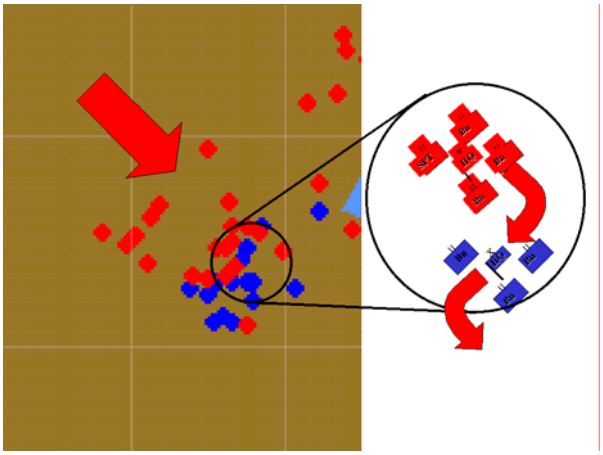

Figure 7. Altering Course of Action Using KB Rules

Since most JWARS unit attributes are recognized as facts, the JWARS rules can be easily associated with specific types of unit by determining what facts the rules employ. This association allows users to build new units and automatically assign appropriate rule sets and actions to those units based on their heterogeneous combinations of unit characteristics. Thus rules can be written to cause combat units to alter course to engage the enemy when such an excursion is not forbidden. Any unit designated as combat, be it armor, infantry, etc. can then inherit the rule. However other rules for small units such as long range reconnaissance patrols and Special Forces teams may override the more general combat rules. At the instance level, very specific rules can be written that override the small unit rules and allow for a suicide mission.

For supporting non-combat units other rules can be assigned that cause these units to alter course to avoid the enemy. Both combat and non-combat units would still be driven by the specific orders issued by their common superior to move to certain objectives or locations, but deviations in the route would be allowed within the constraint of staying generally within the their overall unit formation. Having more detailed information on the friendly force, the opposing force, and the environment would assist the unit in assessing the situation and determining the actions to be taken. Thus, if an infantry unit assessed the likely success of defeating an armor unit based on a simple strength calculation, the armor unit would be expected to win. Yet, if the attacking infantry unit assesses itself as an elite unit, correctly perceives the defending armor unit is poorly trained, and then conducts an air-supported night attack, success could be assessed as likely by the infantry. Note that when the battle occurs, the actual conditions existing at that time will determine the outcome. This approach distinguishes the conditions under which battles are more likely to deviate from the norm and maintains cause and effect rather than randomly selecting some small set of battles that the infantry arbitrarily wins.

Based on earlier JWARS experience, fuzzy rule sets are seen as an excellent tool for complex decisions since they can generate degrees of action rather than just make selections among predefined states. Thus, while a unit may elect to withdraw in the face of a superior force, the speed of withdrawal selected could range over a continuum from zero to the unit's maximum speed based on its perception of the size of the threat and its own vulnerability. Our experience has also been that the number of fuzzy rules needed to perform complex interactions is significantly reduced when compared to equivalent standard rules. Nevertheless, JWARS is still using more standard rules

than fuzzy rules simply because of the maturity of the standard rule sets and their use in making structured decisions. Most subject matter experts (SMEs) find standard rules easier to articulate. In later releases, JWARS will provide improved fuzzy rule generation and editing tools and automated rule testers for the fuzzy rules to remedy some of this bias. JWARS hopes that this will make it easier for the SMEs to use the appropriate tool for the particular decision involved.

One of the key aspects of military units is the cooperative behavior that is expected to occur among units. Because one of the main functions of JWARS is to measure the effectiveness of various force structures, cooperative behavior has to be a highly flexible component of the model. JWARS land units understand that resources such as supplies or long range fires can be obtained from multiple sources, some of which are "better" in certain conditions, but any of which could meet some minimal requirement. Understanding these trade-offs will be a major task of the KBs in the areas of cooperative use of scarce resources, sharing of consumables, and the identification of valid targets, e.g. those which could be struck under certain conditions, but not under others, such as when civilians are in the area.

The primary purpose of assigning rules is to produce credible automated behaviors, but there is also the potential that interesting and unexpected behavior could emerge. If large numbers of runs are made with different random seeds and different combinations of rule sets (especially if learning is allowed), a distribution of outcomes can be observed. Since JWARS has complete traceability and repeatability, it should be possible to determine the conditions that led to the best and worst cases and promote or avoid those conditions as appropriate.

3.3 Related JWARS Developments

JWARS does not depend solely on KBs to represent different behaviors. Every battlespace entity (unit) has an explicit command and control (C2) capability. Supplementing the unit C2 are options to define an explicit unit commander with a specific personality or leadership style. There is also the ability to add plug-ins. These are specific capabilities allocated to a unit such as airborne operations, fire support coordination, maneuver planning, mine clearing, or supply planning. The interplay of these various capabilities provides a rich and still mostly unexplored set of behaviors. Furthermore, it has been suggested that all JWARS C2 be built from plug-ins to allow the user complete freedom to "pick and choose" the elements/capabilities applicable to his or her unit.

3.4 Current Agent Limitations

JWARS units do not negotiate or form temporary coalitions per se, but they do request additional resources or draw on reserves based on perceived and computed priorities driven by the situation. Thus, a unit in contact can request additional fire support and receive it on a priority basis from one or more sources. At the next request, the sources may be different units or employ different weapons, but the support will be provided unless all possible sources have been exhausted. JWARS is interested in negotiation among units on the same side to provide more robust solutions to several of our complex, but very local allocation problems and we believe that the supporting rules can be embedded in the KB.

Also, JWARS does not represent learning at present, but nothing prevents it. Other work related to JWARS such as Stropky, et al (4) describes some of the ways learning might be introduced. Future versions of the JWARS KB may then consider:

- Changing Course of Action (COA) selection criteria weightings based on experience in employing those COAs in various situations during the run of the simulation (modifying the Bayesian priors).
- Increasing or decreasing unit morale based on the experience of the unit in winning or losing battles that it expected to win or lose.

While not learning, per se, the JWARS Commander's Behavior Model already makes better decisions if it has specific information on the opposing commander's intentions and preferences.

4. SUMMARY

JWARS has developed a methodology for generating a rich set of heterogeneous units using agents that operate within a hierarchical organization and act cooperatively to accomplish large scale missions. Individual units can each have their own set of rules that interpret the local information, consider constraints placed on them by higher authority, assess the local situation in the context of the larger situation using their own rule sets, and generate appropriate actions / behaviors as the scenario progresses.

KBs, populated with facts, rules, and actions, are a key element in the behavior of JWARS units, but they are not the only solution to representing credible behaviors. While KBs allow users to insert facts, rules and actions into simulated units and leaders to observe their impact on a modern battlefield, JWARS is amenable to many different approaches to the representation of behavior and behavior generation. JWARS employs an open architecture and welcomes

the participation of the behavioral representation community and the experience of its practitioners in developing methodologies that can be embedded in JWARS to produce credible operational, tactical, and cultural behaviors.

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7. AUTHOR BIOGRAPHIES

LTC Harry Argo (USA) is the Army representative for JWARS and has responsibility for the Land Integrated Product Team. LTC Argo is an ORSA officer with an M.S. in Operations Analysis from the Naval Postgraduate School.

H. Ric Blacksten is a Principal Functional Analyst at CACI. He has over 35 years of modeling and simulation experience. He provides expertise in mathematical modeling, operations research, decision science, systems analysis, and physical system simulation.

Paul Bross is a Project Manager with CACI and a retired US Army Field Artillery officer with combat and operational testing experience. He has an M.S. in OR from the Naval Postgraduate School and has been actively involved in wargames and simulations for over 30 years.

Chuck Burdick is a program manager with Lockheed Martin and currently leads the JWARS Land Warfare Team. He has an MSA in ORSA from George Washington University and over 25 years of experience in simulating military systems. He is a former Army MI officer and retired Colonel in the Army Reserves.

Harvey Graf is a Lead Analyst at the Mitre Corporation. He has more than 17 years of military experience and 8 years of experience in military simulation. Mr. Graf has an M.S. in OR from the Georgia Institute of Technology.

Mihaly Grell is a Senior Simulation Engineer at AT&T GSI. He has over 15 years of experience in the development of military simulation models with particular emphasis on C4ISR.

James Huynh is a Senior Simulation Engineer at AT&T GSI. He has over 7 years of experience in the development of military simulation models with particular emphasis on Land Warfare.

Harvey Johnson is a senior Simulation Engineer at CACI. He has more than 10 years of experience in the use of simulation programming in military models. Mr. Johnson has an M.S. in Computer Science from the Florida Institute of Technology.

Don MacQueen is a Senior Simulation Engineer at AT&T GSI. He has over 25 years of software experience including over 5 years in the development of JWARS with particular emphasis on C4ISR.

John Prince is a Senior Simulation Engineer at CACI. He has more than 8 years of experience in the use of simulation programming in military models. Dr. Prince has an A.B. in Physics from Princeton University and a Ph.D. in physics from the University of Virginia.