Using Fuzzy Cognitive Maps to Assess Multi-Operator Situation Awareness

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A key aspect of modern battlefield environments is the rapid generation and enormous volume of data available to decision makers. Although this data can potentially afford a decision maker an accurate "snap shot" of the emerging situation, it can also produce noise and data clutter that confuses or distracts. When the resulting operation requires individual members of a distributed team to independently make the correct, or, at a minimum, the same interpretation of the available data, volume can become a key impediment to achieving team situation awareness. The problems for decision making become even worse when the team members are not co-located and the responsibilities are distributed. To mitigate adverse effects and to coordinate decision making activities requires tools for developing shared situation awareness within the team. In this paper, the use of fuzzy cognitive maps to model the battlespace for developing shared situation awareness within a team will be discussed.

Team Situation Awareness

Situation awareness can be defined as the "...degree to which every team member possess the situation awareness required for his or her responsibilities." [1, p. 51] Situation awareness can be viewed at three different levels. At its most basic level (Level 1), a decision maker must perceive elements in the environment necessary for understanding the situation. This means that the technology, in a broad sense, is available to provide the "necessary" data and the decision maker has access to it. At a second level (Level 2), the decision maker must comprehend the current situation. He or she must be cognizant that a decision must be made, and how to implement that decision. At the highest cognitive level (Level 3), the decision maker must be able to project future states of different decisions to evaluate or identify one that best achieves the goals for the individual or team.

A team can be defined as having three characteristics: 1) a common goal, 2) interdependence, and 3) specific roles. It can be characterized as a group of decision makers with different responsibilities through whose coordinated action a common goal is achieved. Although the team members may share a common data base, through a common display or by being co-located in the environment, they typically use some subset of the available information for their decision making. If the decisions were completely independent relying on independent subsets of data there would be no problem. But in real team settings, decisions are characterized by overlapping data sets and feedback. Two or more decision makers may both require and use certain data. More importantly one person's decisions may be predicated upon what another person decides to do and vice versa, creating a feedback loop within the decision making structure. Achieving shared situation awareness with this team means that the members have access to the necessary information, including the decisions of the other team members, and that they are assessing it in a coordinated fashion.

In co-located teams, devices for achieving shared situation awareness are developed through three primary mechanisms.

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First, through direct communications team members indicate which data they are currently focusing on and what decisions they are undertaking. Direct communication can be achieved verbally, where literally one team members yells his or intentions at a particular moment, or it can be developed through non-verbal means such as watching what data another team member is focused on. A second device for achieving team situation awareness is shared displays. With a shared display the team members all have access to the same data and, hopefully, interpret it the same. In this way, individual actions undertaken work towards achieving the common team goal and are not incongruent. In a final means, team situation awareness is developed through embedding the co-located team in a common environment, for example, in the same airplane, so the team members each have access to the same environmental information.

A general trend in technology has been an increase in both the capabilities of data acquisition systems and of communications technology. This has lead to an increase in the use of distributed teams with distributed responsibilities that are not co-located. Achieving situation awareness in these settings becomes problematic because 2 of the 3 mechanisms just described are not possible. First, although team members can communicate verbally through a variety of technical means, direct communication as a shared situation awareness device is significantly diminished through the loss of non-verbal communication not easily achieved unless team members are in proximity to each other. Second, the distributed team members are not even necessarily on the same battlefield so a common environment is no longer a means for achieving shared situation awareness. It is now not uncommon for team members to be located in different states or on different continents.

The only remaining device for enabling situation awareness is through the shared displays and the information that is presented. The challenge for achieving shared situation awareness in distributed teams is to identify ways in which data and decisions can be presented to team members that insure they all interpret the emerging, dynamic battlespace environment the same and work towards achieving the same goal. And critical to this is the recognition of the feedback nature of the decision making process in the distributed teams. In the past, there has typically been a commander within the decision making structure in a military environment that has in some sense "imposed" situation awareness on a distributed team by interpreting the situation and providing the team members with the goals and tasks that they must accomplish. With the pace of a modern battlefield and the speed at which it evolves, having a central command act as a "clearinghouse" for developing situation awareness has become a bottleneck to rather than an enabler of team situation awareness. The real challenge to achieving situation awareness in distributed teams is to develop methods and mechanisms for sharing information, including information about decisions being made, so that all team members interpret the emerging battlespace the same and understand their role in achieving the common goal.

Fuzzy Cognitive Maps

To affect all three levels of situation awareness in a distributed team, a model is needed of the decision making process of all the team members that can incorporate a variety of data, information, decisions in the team setting and accurately reflect the tradeoffs necessary for identifying the optimal or best courses of action to achieve the team goal. Especially important, it must be able to model or effectively incorporate feedback within the decision making process. Such a model, to be truly useful, must be flexible, must be updatable in real time, and must provide the decision makers with a way to project changes in states for various choices or decisions they can make. This gives the team the ability to identify an optimal or best course of action to achieve the common goal.

In this paper, fuzzy cognitive maps will be examined as a means for modeling the decision making process in distributed teams with distributed tasks and distributed knowledge. A fuzzy cognitive map is a di-graph with fractional edge strengths that models the cause and effect relationships that a decision maker postulates about the solution space for a problem. [2,3,4] Each node in the map represents a cause or effect, with a directed edge between two nodes indicating a causal relationship. Edge strengths in the map are values on the interval [-1,1] with 1 indicating full causality (an increase in A causes an increase in B), -1 indicating inverse causality (an increase in A causes a decrease in B), and fractional values (negative or positive) indicating partial causality. This last case models situations such as "an increase in A *somewhat* causes an increase in B".

Nodes in a fuzzy cognitive map must represent variable quantities rather than instantiations of a particular concept. As such nodal values are restricted to the single values of -1 (decrease in value for concept), +1 (increase in value for concept), and 0, (no change in value for concept). A positive value represents an increase rather than a presence of the concept modeled by the node. Decisions (choices) are represented in the map by binary nodes, where 0 represents the absence of the decision and +1 represents it presence.

The fuzzy cognitive map can be used to infer the state of the system being modeled by the nodal values that occur after a set of "inputs" is applied and the map equilibrates. [8] A tradeoff is involved in designing and using a fuzzy cognitive map. Because concepts are represented in the map by nodal values rather than numerical quantities, a common numerical scale does not have to be developed for comparing conceptually different nodes. The map compares qualitative states of quantities to qualitative states of quantities, rather than numerical measures of concepts to numerical measures of concepts. This provides fuzzy cognitive maps with the distinct advantage of being easilty able to compare "apples to oranges". Very different types of concepts, such as environmental data, decisions being made, enemy intentions, and the status of weapons, can each be incorporated into the map and used in the inference process. The tradeoff, though, is that the fuzzy cognitive map can not determine numerical values for an underlying concept represented by a node. A map might infer that a *large* number of F-15's should be tasked, but it can not directly infer that 12 F-15's should be tasked. [7]

An important attribute of the fuzzy cognitive map is the ease with which several maps, independently constructed can be combined to produce a composite map that better reflects the overall situation than any map individually. Each individual map may only model a subset of the overall problem or reflect a portion of the available information. Since a fuzzy cognitive map compares states of attributes to states of attributes, individual maps can be combined by overlaying them. Common nodes are identified and used as anchors for combining the maps. Other nodes are simply added from these common nodes in such a way that the result reflects the connections identified in the individual maps. This ease of combining separate maps has great potential utility in using FCM techniques to construct an overall model of the situation that reflects the vantage points of the individual team members. The combined map can be used as a global or normative model to project future states, evaluate alternate courses of action and to identify potential conflicts in the decision processes of the individual team members.

Evaluating Fuzzy Cognitive Maps

To evaluate the efficacy of using fuzzy cognitive maps as a model for understanding the situation awareness of distributed teams with distributed information, a group of students was divided into teams and assigned specific missions in a synthetic task. The task used was one of a hypothetical North Korean attack on South Korea in which SCUD missiles were used. Each student team was given responsibility for constructing rules of engagement for a particular asset that would likely be involved in any SCUD-hunting missions. For the scenario used, three teams, two of two members each and one of one member, participated. Each controlled (or tasked) one of the following air force assets: U-2 surveillance aircraft, F-15 Hunter/Killer groups or F-15's diverted from combat air patrol to attack a TEL.

The task was defined using the "Day After..." methodology developed at the RAND Corp. [9] This methodology provides the participants with a variety of background information pertinent to the problem, and has them walk though an evolving crisis. As they worked through the crisis they constructed a fuzzy cognitive map of the way that they would task the air force asset under their control. Although all three teams were provided with the same background information, they were not provided with the rules and models the other teams developed. The goal was to evaluate how well the individual models (as defined by a fuzzy cognitive map) would, when combined, produce an overall "team" model. The three resulting maps are presented in the figures at the end. A sequence of nodes in one of the map represents a chain of causal reasoning about how an environmental condition or a decision will affect other attributes. For example (from the map for Diverting F-15's from CAP), night would decrease the chances of finding the TEL which would decrease the ability to attack it. A decrease in the ability to attack the TEL would decrease the chances of destroying it which would decrease the desirability of diverting an F-15 from CAP to attack it. [5]

Results

Each of the three maps involved overlap. There were nodes common to two or all three maps, given in table 4. For example, the TEL fleeing was common to all three maps. Good and Bad weather was common to two. Not only were some nodes common but several of the models required input or knowledge of the decisions by another team. For example, tasking a Hunter/Killer group required knowledge of whether a U-2 had been tasked to locate and monitor the movements of the TEL. Likewise, the U-2 team required knowledge of whether an asset had been tasked that could attack the TEL should the U-2 be sent to monitor it. These nodal paths provided multiple feedback between the two maps that could affect the decisions made.

Combining the fuzzy cognitive maps produces a synthesized model of the decision making space that incorporates the attributes each of the team members identifies as important. This combined map can be used as a normative model or representation of the situation awareness of the team, i.e. it is a global snap shot of the battlespace from several different perspectives. It includes feedback and overlap. Identifying nodes and paths in the map that represent these two characteristics identifies both where the team *cooperates* to achieve goals, and where potential problems may exist. For example, there is no direct link between *Having a Sufficient Response Time* from the Tasking a Hunter/Killer Map and *Tasking a U-2* from the Tasking a U-2 map. But when the maps are combined an indirect path exists: *Sufficient Response Time → Sneak Attack → Multi-Front Attack → Tasking Multiple Hunter/Killer Groups → Attack TEL →Task U-2*. These hidden or indirect relationships that emerge only when the composite map is constructed represent the value added of a team effort over an individual effort. Additionally, they can represent significant constraints on the potential actions of one decision maker. Decisions by one team member can hamper or limit the available actions of another team, and not always in an obvious way. Constructing a composite fuzzy cognitive map affords a vehicle for identification of these global relationships.

A composite fuzzy cognitive map can be used in several ways in the context of the situation awareness of a distributed team. Specifically:

- The map represents a global model or representation of the battlespace that incorporates decisions, environmental attributes, weapons capabilities, etc. This model can be used to understand the effect and the effectiveness of decisions.
- The model can be used to help different team members understand how their actions affect another's actions. A key feature of a composite map is that specialized knowledge is needed to construct it, but not to understand it. The map can be used as a communications bridge between team members with different knowledge.
- The model can be used as a software mediator for managing data and decisions. In past military epochs situation awareness was typically imposed by a centralized command and control structure that had access to all relevant data. This central command structure has now become a key bottleneck in the decision making process because of the increased pace of operations in a modern battlespace. A composite fuzzy cognitive map can be used as a software mediator to distribute data and determine optimal (or satisfactory) courses of action, and, consequently, foster a common understanding of the emerging situation among team members.
- A fuzzy cognitive map can be used as a diagnostic tool to identify potential incongrunencies in the decision making process of distributed teams with distributed knowledge. It is possible that if, left in isolation, a team member could evaluate the emerging situation from their vantage point, and make a decision orthogonal to the situation or the decisions of others. A composite map, because of feedback in the causal loops, may identify an alternate, more productive course of action for the team.

Using a composite fuzzy cognitive map as a diagnostic tool for identifying potential friction in team decision making will be evaluated in the context of the SCUD-hunting task used in this paper. The initial values for the scenario used are given in table 8. The values chosen were selected to try to give a situation where the U-2 surveillance aircraft would not be tasked, primarily because of the threat from enemy defenses. Applying these values to the *composite map* and inferring output values yielded the following result. A U-2 should not be tasked, nor should a Hunter/Killer group. The TEL flees and the chances of destroying it are reduced.

If the same initial conditions are applied to the individual map for tasking a U-2, the same results for the composite map are inferred. The U-2 should not be tasked. But if these initial conditions are applied to the individual map for tasking a Hunter/Killer group, a different result is inferred. Regardless of whether or not the U-2 is tasked, the inferred result from this map is that a Hunter/Killer group *should be* tasked, a result different from the projected decision from the composite map.

The composite map involves feedback, so certain effects are reinforced while others are dampened. This has the net result that the global conditions are such that a Hunter/Killer group should not be tasked. From the isolated view point of the Hunter/Killer group, as determined by its fuzzy cognitive map, a group should be tasked, but from a the more global viewpoint of the composite map, which includes two additional vantage points, it should not be tasked. Using a composite fuzzy cognitive map to identify and understand these discrepancies in decisions can be an important tool in improving the situation awareness of distributed teams and, consequently, team decision making.

Figure 1. Fuzzy Cognitive Map for Tasking F-15 Hunter/Killer Groups

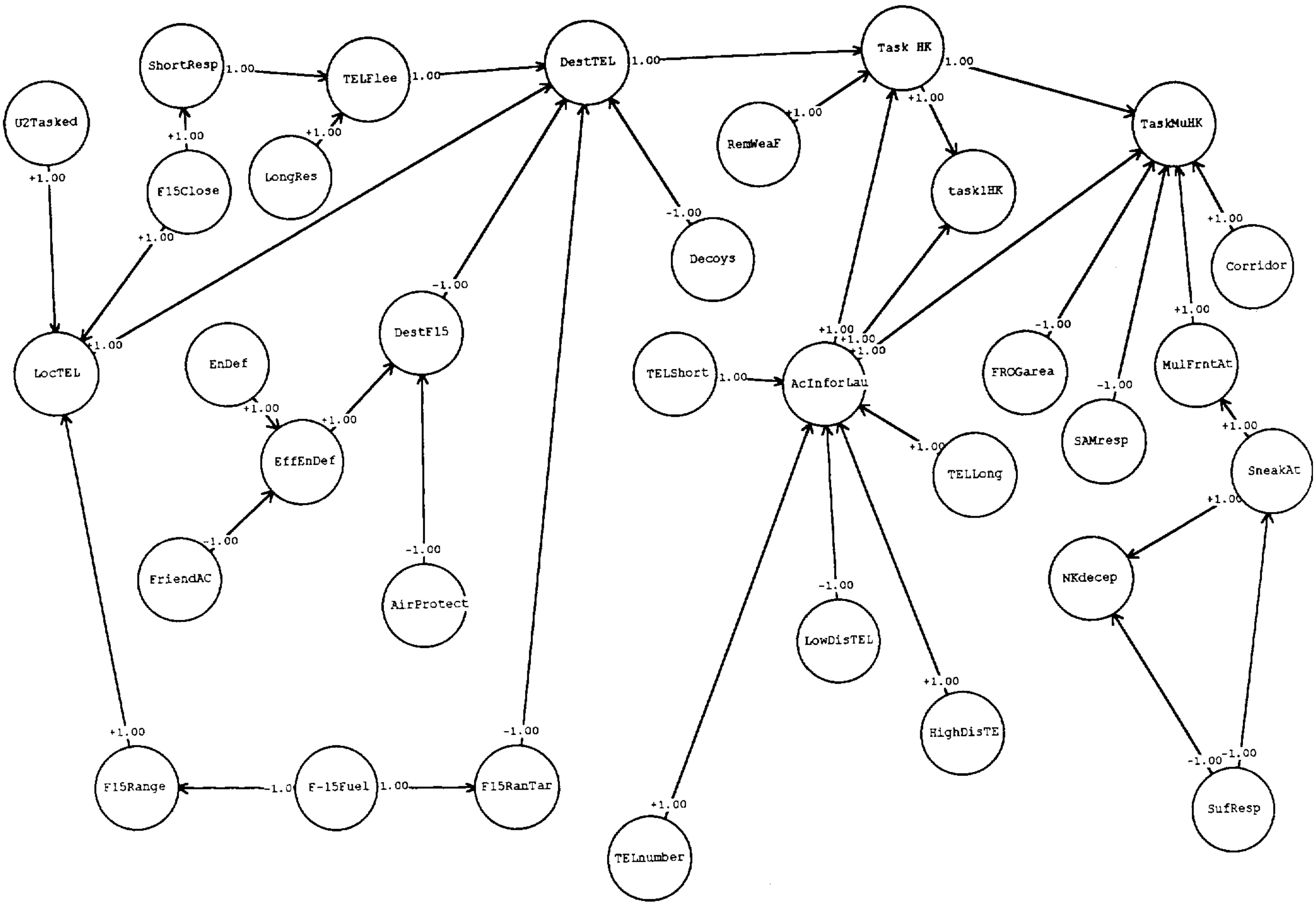

Table 1. Nodal Descriptions for Tasking Hunter/Killer Group Map

Node Mnemonic	*Description*
U2Tasked	U2 tasked
LocTEL	Ability to locate and monitor TEL
F15Range	Patrol range of F15
F-15Fuel	Fuel remaining for F15
F15RanTar	F15 range to target TEL
AirProtect	Availability of air protection for F-15
FriendAC	Other friendly aircraft in area
EffEnDef	Effectiveness of enemy defenses
EnDef	Enemy defenses in area
DestF15	Chances of destroying F15
F15Close	F15 close to TEL
LongRes	Long response time
ShortResp	Short response time
TELFlee	Chances of TEL fleeing
DestTEL	Chances of success of destroying TEL
Decoys	Presence of TEL decoys
RemWeaF	Remaining weapons load on F15
Task HK	Choose to task Hunter/Killer group
task1HK	Task one Hunter/Killer group
TELShort	Short coverage range of TEL's missiles
AcInforLau	Accuracy of information about launch area
TELLong	Long coverage range of TEL's missiles
LowDisTEL	Low accuracy in distinguishing decoys
HighDisTE	High accuracy in distinguishing decoys
TELnumber	Number of TEL's in area
SufResp	Sufficient response time for Patriot batteries
Nkdecep	Possibility of North Korean deception
SneakAt	Vulnerability to sneak attack
MulFrntAt	Possibility of multi-front attack
SAMresp	Response time for Patriot SAM battery
FROGarea	Coverage of FROG attack area
Corridor	Desire to create TEL-free corridor
TaskMuHK	Task Multiple Hunter/Killer groups

Table 2. Nodal Descriptions for Tasking U2 Map

Node Mnemonic	*Description*
TaskU2	Task U2
ImpCurMiss	Importance of mission U2 is currently on
AttackTEL	Availability of assets to attack TEL
Other U2	Availability of other U2's in theater
U2DesTEL	Chances of U2 being destroyed at TEL
U2Det	Detectability of U2 by enemy
HvEnDef	Heavy enemy defenses in route
LghtEnDef	Light enemy defenses in route
DesU2RT	Chances of U2 being destroyed before it reaches TEL
ShPatrol	Short patrol time for U2
LongPatrol	Long patrol time for U2
OverlapPA	Overlap of patrol areas
ShTransTm	Short time to reach TEL area
LnTransTm	Long time to reach TEL area
LtDefTEL	Light enemy defenses at TEL
HvyDefTE	Heavy enemy defenses at TEL
TELFlees	Chances that TEL can flee or evade
NumTEL	Number of TEL launchers in launch area
ImposTer	Impossible terrain to locate TEL in
FlatTerrai	flat terrain to locate TEL
DetectTEL	Detectability of TEL
BadWeath	Bad weather
GoodWeat	good weather
SensorUsa	U2 sensor usability

Figure 2. Fuzzy Cognitive Map for Tasking U2 Team

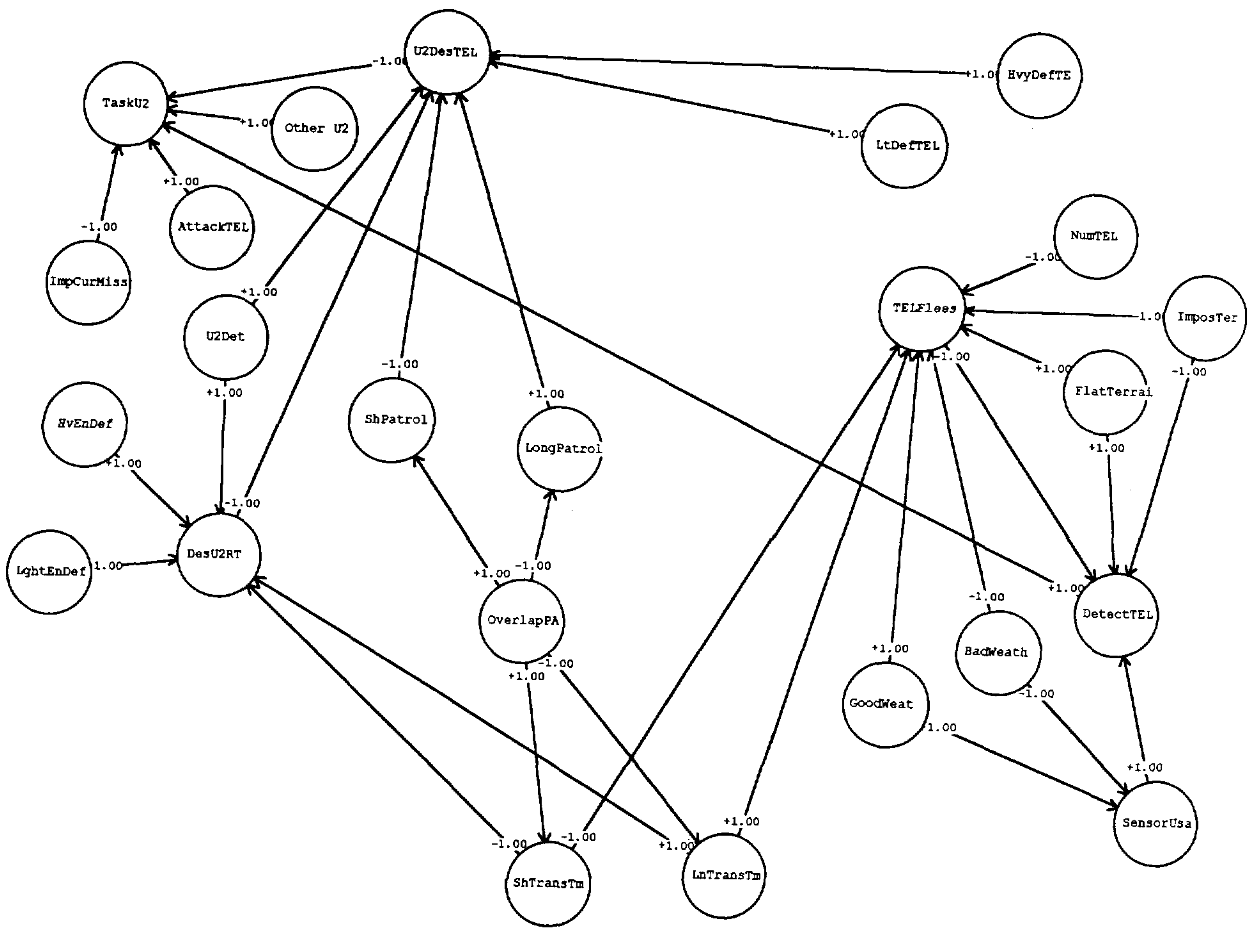

Figure 3. Fuzzy Cognitive Map for Tasking Other F-15 Assets

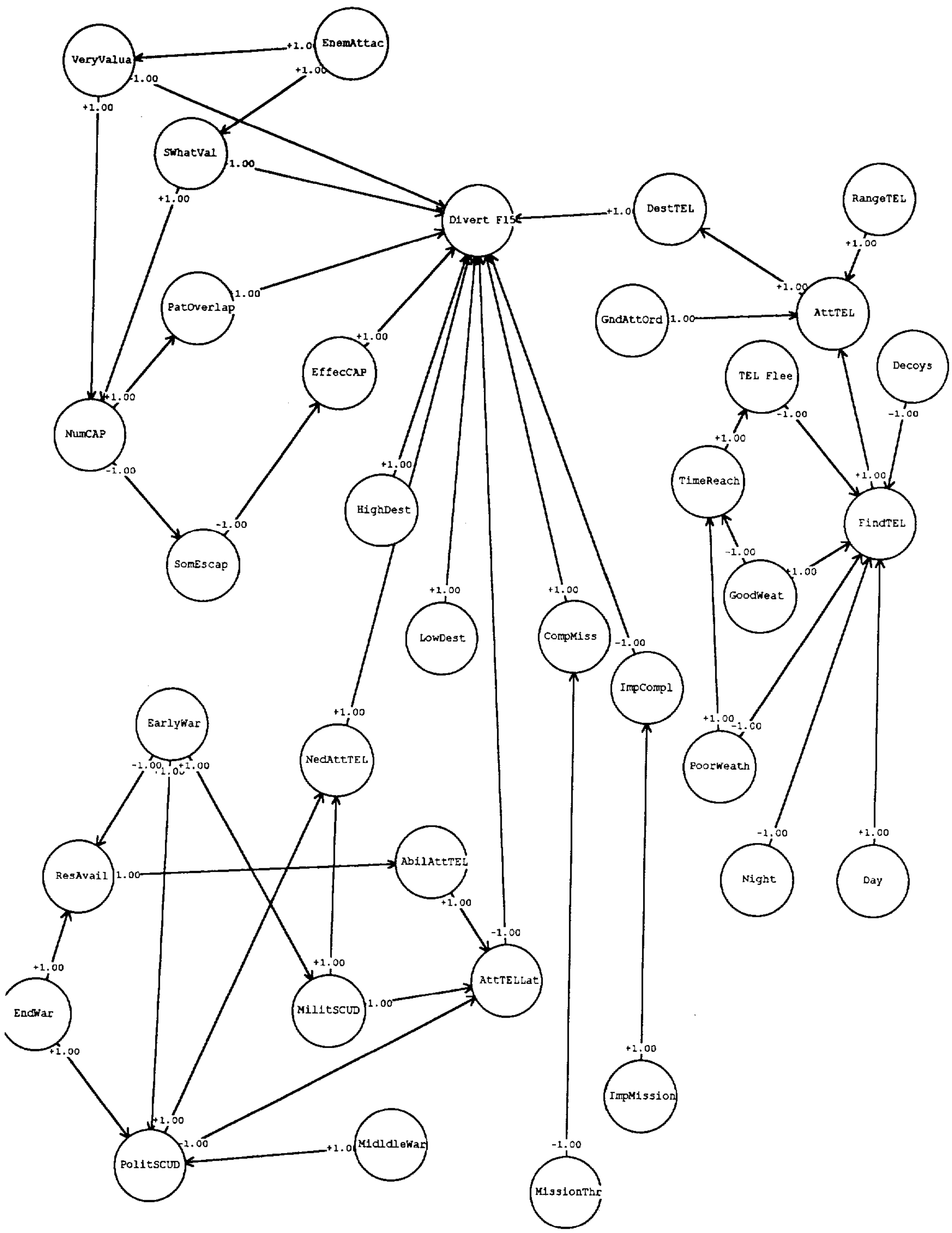

Table 3. Nodal Descriptions for Tasking Other F-15 Assets Map

Node Mnemonic	*Description*
VeryValua	Very valuable asset being protected
EnemAttac	Chances of enemy attack
SWhatVal	Somewhat valuable asset being protected
NumCAP	Number of aircraft on CAP
SomEscap	Chances of some enemy aircraft getting through
PatOverlap	Overlap of CAP patrol area with TEL launch area
EffecCAP	Effectiveness of CAP
Divert F15	Divert F-15's from CAP to attack TEL
High Dest	High value of destroying TEL
Low Dest	Low value of destroying TEL
CompMiss	Chances of completing mission
ImpCompl	Importance of completing mission
ImpMission	Importance of mission F-15 is escorting
MissionThr	Threat against mission
EarlyWar	Early stage of war
NedAttTEL	Need to attack TEL
ResAvail	Amount of resources available
AbilAttTEL	Ability to attack TEL later
AttTELLat	Luxury of attacking TEL's later
MilitSCUD	Military value of SCUD attack
EndWar	Near end of war
PolitSCUD	Political value of SCUD attack
MiddleWar	Middle stage of war
DestTEL	Chances of destroying TEL
RangeTEL	Range to TEL for F-15's
AttTEL	Ability to attack TEL
GndAttOrd	Ground attack ordinance
Decoys	Presence of decoys
TEL Flee	Ability of TEL to flee
TimeReach	Time of F-15 to reach the target
FindTEL	Ability to find and locate TEL
GoodWeat	Good weather
PoorWeat	Bad weather
Night	Time of day is night
Day	Time of day is day

Table 4. Nodes Common to Maps

	Map	
Tasking U2	*Diverting F-15*	*Tasking Hunter/Killer Group*
Task U2		Task U2
Good Weather	Good Weather	
Bad Weather	Bad Weather	
TEL Flees	TEL Flees	TEL Flees
Number of TEL's		Number of TEL's
Enemy Defenses		Enemy Defenses
Task F-15	Task F-15	Task F-15
	Destroy TEL	Destroy TEL
	Presence of Decoys	Presence of Decoys
	Locating TEL	Locating TEL

Table 5. Inputs for Tasking Hunter/Killer Groups Map

U2 tasked
Fuel remaining for F15
Availability of air protection for F-15
Other friendly aircraft in area
Enemy defenses in area
F15 close to TEL
Long response time
Short response time
Presence of TEL decoys
Short coverage range of TEL's missiles
Long coverage range of TEL's missiles
Low accuracy in distinguishing decoys
High accuracy in distinguishing decoys
Number of TEL's in area
Sufficient response time for Patriot batteries
Response time for Patriot SAM battery
Coverage of FROG attack area
Desire to create TEL-free corridor

Table 6. Inputs for Tasking U2 Map

Importance of mission U2 is currently on
Availability of assets to attack TEL
Availability of other U2's in theater
Detectability of U2 by enemy
Heavy enemy defenses in route
Light enemy defenses in route
Overlap of patrol areas
Light enemy defenses at TEL
Heavy enemy defenses at TEL
Number of TEL launchers in launch area
Impossible terrain to locate TEL in
Flat terrain to locate TEL
Bad weather
good weather

Table 7. Inputs for Tasking other F-15 Assets Map

Very valuable asset being protected
Chances of enemy attack
Somewhat valuable asset being protected
High value of destroying TEL
Low value of destroying TEL
Importance of mission F-15 is escorting
Threat against mission
Early stage of war
Near end of war
Middle stage of war
Range to TEL for F-15's
Ground attack ordinance
Presence of decoys
Good weather
Bad weather
Time of day is night
Time of day is day

Table 8 Initial State Values for a Test Scenario for the Task

All nodes not listed below had initial values of 0.

Node Values of 1	*Node Values of -1*
EnemAttac	GndAttOrd
HighDest	OtherU2
RangeTEL	
Night	
ImposTerra	
LongResp	
ImpMission	
PoorWeath	
EarlyWar	
MissionThr	
HvDefTEL	
HKF15Clos	
AirProtect	

References

[1] M. Endsley and W. Jones. *Situation Awareness, Information Warfare and Information Dominance.* USAF Armstrong Laboratory. Technical Report 97-01. 1997. (Draft)

[2] B. Juliano and W. Bandler. *Tracing Chains of Thought.* Springer-Verlag. Heidelberg, Germany. 1996.

[3] B. Kosko. "Fuzzy Cognitive Maps." *International Journal of Man-Machine Studies.* 24. 1986. P.65-75.

[4] Kosko. "Adaptive Inference In Fuzzy Knowledge Networks". *IEEE International Conference on Neural Networks.* June. 1987. P.II-261-268.

[5] M. Mandeles, T. Hone and S. Terry. *Managing Command and Control in the Persian Gulf War. Praeger Press.* West Port, CT. 1996.

[6] K. Perusich. "Information Warfare: Radar in World War II as an Historical Example". *Proceedings of the International Symposium on Technology and Society 1997.* P. 92-99.

[7] K. Perusich and M. McNeese. "Using Fuzzy Cognitive Maps to Define the Search Space in Problem Solving". *Advances in Human Factors/Ergonomics. 21A Design of Computing Systems: Cognitive Considerations.* G. Salvendy, M. Smith and R. Koubek (Ed.). Elsevier. 1997. P.805-808.

[8] K. Perusich and M. McNeese. "Using Fuzzy Cognitive Maps for Data Abstraction and Synthesis in Decision Making". *Proceedings of the Annual Meeting of the North American Fuzzy Information Processing Society.* Syracuse, NY. 1997. P. 5-9.

[9] R. Molander, A. Riddle, and P. Wilson. *Strategic Information Warfare-A New Face of War.* Rand Corp. 1996.