Abstract

This paper describes a methodology for converting an influence net to an executable model, implemented using the Colored Petri Net formalism and tools, so that it can be used to assess the impact of a set of controllable events or actions on outcomes of interest; specifically the impact of various sequences and timing of those actionable events. With this methodology, alternative courses of action, first defined using influence nets, can be refined by adding sequence and timing information for analysis and comparison. The techniques developed offer a means to integrate intelligence and operational planning models to improve course of action development. The paper includes a description of the automated algorithms that convert an influence net to a Colored Petri Net and illustrates how that model can be used for the analysis of alternative courses of action.
In the command and control environment, planning and selecting specific courses of action to achieve objectives and goals involves two types of modeling and analysis activities (Figure 1). The first involves models that attempt to assess potential events and outcomes based on incomplete and uncertain understanding of both physics based and perception based processes. Such activity is primarily the forte of intelligence analysts. Probabilistic modeling techniques that provide inferences are often used to suggest what outcomes might occur given sets of controllable actions and uncertain exogenous events. The second type of activity, planning, involves the generation and evaluation of detailed actions and activities to accomplish the mission goals. In general detailed models and algorithms are available for planning the courses of action to be taken. These two classes of activity involve different ways of viewing problems, and the models created have different characteristics. In many cases, the executable models used in planning require parameters that can be derived from the probabilistic models. It follows, then, that being able to place both modeling techniques in a common environment can enhance the overall planning process. This research concentrated on influence nets which are one type of probabilistic modeling. In particular, the software application, Situation Influence Assessment Module (SIAM) developed by SAIC [Rosen and Smith, 1996] was used. Design/CPN, was chosen as the target environment into which the influence net models would be converted by an automatic algorithm written using ML code and many of the functions built into the Design/CPN application. The remainder of this section provides a brief description of Influence Net modeling, motivation for the research, and a statement of the problem. Section 2 describes the conversion algorithm including design considerations and decisions. Section 3 provides an overview of a process for course of action development and evaluation using influence nets and their derivative executable models. Section 4 provides an example that illustrates the process. The last section summarizes the results of this effort and includes a brief discussion of future directions.
1.1 What is an Influence Net

Influence nets are an extension to traditional Bayesian inference nets, sometimes called Bayesian belief nets or causal probability networks. Bayesian nets have both a graphical and a mathematical component and are used to model complex domains where uncertainty exists. They are directed acyclic graphs that represent the factorization of joint probability distributions of a set of random variables. They include an inferencing procedure for updating the joint probability distribution via Bayes rule as new information is received about any of the random variables. Thus they can be used as powerful modeling constructs for diagnostics and estimating outcomes given evidence. Because their construction requires the creation of marginal and conditional probability tables, they tend not to be easily accessible to decision makers not familiar with probability theory. Influence nets were developed to extend the traditional Bayes net structure and allow the creation of useful models by analyst unfamiliar with probability theory or who are unable to spend the time needed to fully specify a complete Bayesian net.

Influence net modeling incorporates an intuitive graphical influence diagramming technique for model construction. The SIAM implementation used in this investigation automatically creates a Bayesian model that allows for rigorous analysis using non mathematical inputs from the analyst. To construct an influence net, a modeler creates "influence nodes" that depict events that are part of a set of cause-effect relationships appropriate to the situation being modeled. The modeler also creates influence links between the nodes to graphically illustrate causal relationships between events. Each influence link can either be promoting or inhibiting, as identified by the terminator of the connecting link (arrow head for promoting, ball for inhibiting).

Figure 2 shows a simplified and hypothetical example of the topology of an influence net that might be created by intelligence analyst to assess a potential military situation and evaluate the effectiveness of a combination of diplomatic and military options. This net represents a situation where a Country B is in a posture that is threatening to its neighbors, creating instability. Country G is contemplating conducting a covert mission to destroy a key facility in Country B. If successful, the mission should reduce the confidence of the leader of Country B. The covert mission will be more effective if it can occur at the same time as a diplomatic mission visits a neighboring country. Additional influence will occur if the international community threatens sanctions against Country B.
With SIAM, in order to generate the underlying quantitative marginal and conditional probability values, the modelers indicate, through a graphical user interface (GUI) the “strength” of each influence link to either promote or inhibit the effect event at the head of each link given the event at the tail. This approach is based on "Causal Strengths" logic [Chang, et. al. 1994] including an algorithm for converting causal strengths to marginal and conditional probability transition matrices to evaluate the cumulative likelihood of any event in the influence net using traditional probability calculations. Once constructed, influence nets can be used by analysts and decision makers to examine events over which they have some control to determine which events have the best chance of creating the outcomes desired by the decision maker.

1.2 Motivation for this effort

Influence nets produce static equilibrium models that relate cause to effect. There is no time or dynamic behavior captured in such models. They are most useful in assessing situations involving perceptions, rationale, and decisions. They are particularly useful if
there is no underlying "physical" phenomenon that can be represented in analytical and executable dynamic models or if the underlying physical phenomena are not known.

One of the prime uses of influence nets is the evaluation of chains of causes and effects to determine which actions have the greatest likelihood of causing the desired outcome. In this sense, the influence net helps a decision maker decide what should be done. Detailing how the actions should be executed, in many cases, will involve the time-phasing of the actions. This can be modeled more effectively by a discrete event dynamical system. In many cases, such models require input parameters that can be estimated from influence nets. This effort was motivated by the notion of converting influence net models into an environment that can incorporate discrete event dynamical models so that both situation assessment models and dynamic models of courses of action can be interconnected to bring together the advantages of both modeling techniques into a single modeling environment. With such a process, it will be possible for analysts familiar with situation assessments to create influence nets in the environment with which they are most familiar and then to transfer their work in an automated way into an environment suitable for the execution of discrete dynamical models for evaluation of the selected courses of action.

1.3 Statement of Problem

The objective of this research was to design, develop, and test an algorithm that could take an output file from an influence net modeling software application and automatically generate an executable Colored Petri Net model. This model could then be interconnected to other executable CPN models. The Colored Petri Net model would perform the same forward probability propagation calculations that the influence net application performs. In addition, the algorithm should allow time delays to be added to the probability propagation at various nodes, allow easy input of marginal probabilities to the initial nodes for evaluating impact of different events, and allow the user to designate nodes for which a time history of change in probability could be collected for analysis.

2 Design of the Conversion Algorithm

In this effort, a UNIX-based influence net modeling application called Situation Assessment Module (SIAM) developed by Rosen and Smith (1996) was used. The design process started by understanding both the information available within a SIAM generated model and the calculations used by SIAM to propagate marginal probabilities given a change in probability of the initial events in the influence net. This understanding was
used to design an output file that would be generated from SIAM and design a set of Colored Petri Net subnets that would replicate the probability propagation process. A multi step process for reading that file and converting it to a Colored Petri Net that would implement the forward probability propagation calculation was then developed. The remainder of this section describes the SIAM processes and information followed by a brief description of the multi step conversion algorithm including description of the Colored Petri Net that is created.

2.1 Influence Net Calculations and Export Information

The initial requirements for the design of the conversion algorithm focused on the probability calculations of SIAM that would be replicated in the Colored Petri Net. The calculation to be implemented is as follows.

Each node in the influence net represents some variable of interest and the variable is Boolean, in that it represents a logical statement that is either true (T) or false (F). Probabilities are associated with each node $X$ expressed as a marginal probability $P[X]$. For each node in the influence net that has $n$ parents ($n > 0$), let $Q_i$ be the $i^{th}$ set of parent states. A set of conditional probabilities, $P[X|Q_i]$, can be defined for each set of parent states of node $X$. SIAM uses the simplifying assumption that all the parent states are independent. With this assumption, letting $P[q_j \in Q_i]$ be the marginal probability of the $j^{th}$ parent state in $Q_i$, then the marginal probability of that node $X$ is

$$P[X] = \sum_{i=1}^{2^n} \left[ P[X \mid Q_i] \times \prod_{j=1}^{n} P[q_j] \right]$$

$q_j \in Q_i$

Given this calculation, the following information was needed from SIAM to create the conversion: for each node in the influence net, the name of the node and its identification number, its position in $x$ and $y$ coordinates on the diagram, the number of parents of the node, its initial marginal probability, and a vector of the $P[X|Q_i]$ representing the complete set of conditional cases for that particular node. For example a node $X$ with four parents, $A$, $B$, $C$, and $D$, would have $2^4 = 16$ conditioning cases as shown in Figure 3.
For this effort, a special export routine was added to SIAM by Rosen and Smith that generates a text file with the above information for any influence net created in SIAM. Figure 4 shows an example of part of such an export file.

```
"Causal Network Nr" //Net Nr
95 // Number of Nodes

1 //ID of M1 //N=111 //X=244
"County A employs ECF/mother" //Name of
0.53253 //Marginal Belief of M1
1 //Number of Nodes
00 //Baseline //County B random sample
0.00458 //1000=0
0.99542 //9000=1

2 //ID of M1 //N=111 //X=244
"UH file inspection 89p" //Name of Nodes
0.04458 //Marginal Belief of M1
0 //Number of Nodes

3 //ID of M1 //N=111 //X=244
"UH was on the scene" //Name of M1
0.04458 //Marginal Belief of M1
0 //Number of Nodes

4 //ID of M1 //N=111 //X=244
"Lack of County Director at "merdeco" //Name of Nodes
0.13483 //Marginal Belief of M1
3 //Number of Nodes
1 //Node 2 "County A employs ECF/mother"
2 //Node 3 "UH had no ambulance"
3 //Node 3 "UH had no ambulance"

presort
0.00775 //415.56.3=0(F,F,F)
0.38079 //415.56.3=0(F,F,F)
0.00214 //415.56.3=0(F,F,F)
0.1247 //415.56.3=0(F,F,F)
0.0129 //415.56.3=0(F,F,F)
0.00341 //415.56.3=0(F,F,F)
0.00046 //415.56.3=0(F,F,F)
0.00044 //415.56.3=0(F,F,F)
```

2.2 Overview of the Conversion Algorithm

The algorithm for converting this export file was written in Design/CPN 3.0 using ML code. It has seven steps:

1. Read the text file from the Influence net application and initialize variables.

2. Draw a page containing auxiliary boxes and arrows that replicate the topology of the influence net. Use Design/CPN functions to evaluate this net and classify nodes into three categories: initial, intermediate, and terminal nodes.
3. Partition the net into sets of nodes that will be placed on individual pages in the Colored Petri Net.

4. For each page, create and interconnect subnets for each node of the original influence net that perform the probability propagation and updating for each node of the influence net.

5. Designate fusion places that interconnect each of the pages with so that the topology of the Colored Petri Net is the same as the influence net.

6. Create a control panel page that allows the initial nodes of the net to be given marginal probability values and provides places to collect a history of the changes in marginal probability of nodes designated by the analyst.

7. Initialize the net by reading a file containing time delay information for each node.

The ML code is contained in auxiliary boxes on a page in Design/CPN. Each box of code is executed one box at a time until the complete CPN model including the control panel page has been created. At the end of each step, an appropriate dialog box appears indicating the step has been completed.

Once the Colored Petri Net has been constructed, a syntax check is made and the model is switched to the simulator mode. Once in the simulator, the model can be executed using different markings in the control panel that represent probabilities of the input nodes. The resultant history of changes in probability of the designated nodes is contained in the output places and can be saved as text files for analysis using a spreadsheet program such as Excel. In addition to evaluating the influence diagram in the Colored Petri Net, existing Design CPN models representing the details of courses of action can be loaded into the appropriate pages of the influence net model and connected using fusion places.
3 Methodology for Developing and Evaluating Courses of Action

The ability to automatically transform an influence net into a Colored Petri Net enables the integration of intelligence analysis tools and techniques with those used by planners for developing course of action. Figure 5 provides a conceptual view of the process. Given a politico-military situation, intelligence analysts develop a model of the socio-political interactions that affect the decision making of the countries involved, using SIAM or other influence net tool. Typically, it may take a month to initially build such a model. Once created, the model can be updated fairly quickly as the situation unfolds. This activity is depicted in the upper shaded rounded box of Figure 5.

Once the influence net is constructed, the intelligence analyst uses SIAM to conduct sensitivity analyses to relate potential actionable events to the outcomes of interest. With SIAM, this can be done in a matter of minutes. The output of these sensitivity analyses is a set of pressure points, those actions that have the best chance of causing the outcomes that are desired. These pressure points serve the basis for developing the courses of action.

The SIAM model is then converted to an executable model for course of action development and evaluation, using an automated algorithm like the one developed in the research. As part of the conversion process, both the intelligence analyst and the planners add temporal data and rules to the Colored Petri Net to capture the dynamics of the situation and the potential actions identified as pressure points in SIAM. The intelligence analysts, in collaboration with the planners, develop and incorporate scenario information...
into the executable model that includes the potential timing of exogenous events contained in the model.

In general, the SIAM model will have revealed combinations of actions that are expected to yield the desired outcomes. As depicted in the second rounded box of Figure 5, the executable model is used first to analyze impact of different sequences of the actions, to eliminate the least effective ones. The planners use the most promising sequences to construct time phased courses of action for evaluation. Given a sequence, the planners use the executable model to experiment with the time differences between actions in the sequence to determine the sensitivity of the outcomes to event timing.

Figure 6 is a flow chart that depicts relationship between the steps of the methodology and the tools used to support the steps. The activities in the boxes shaded in gray are conducted by intelligence analysts using SIAM, and the activities in the unshaded boxes are conducted by the planners using the executable models of the influence net.

The methodology employs both analysis and synthesis. With SIAM, the intelligence analysts first analyze the situation to include potential operations concepts. The sensitivity analysis helps in the synthesis of an operational concept by identifying which elements best contribute to the objective. The evaluation of the sequences of actions is a winnowing process to reduce the number of candidate courses of action to be considered. Finally, the detailed timing analysis indicates the size of event time windows that can be important factors in the selection of the final plan.
One of the advantages to the converting influence nets to executable models is that it allows the planners to integrate existing operations models with the intelligence model. Once the best sequences are determined and the sensitivity to time windows are known, planners can incorporate that information in existing operational models that are used to generate detailed plans specifying the timing of tasks and activities and allocate specific resources to those tasks. The operational models may reveal constraints on the timing of events that can be fed back into the executable model of the influence net for further assessment. The final outcome of the process is a detailed plan ready of approval and execution. Figure 7. illustrates the overall concept.

4 Example

The following example illustrates the procedure for creating an influence net of a politico-military situation, using it to select high pay-off actionable events, converting the net to a CPN, and executing the CPN to collect data for course of action evaluation.

In this example, a hypothetical country, Witmania has undertaken a program to develop and produce weapons of mass destruction (WMD). Country G, the good guys, seeks actions to cause Witmania to stop its program. The intelligence community of country G has sufficient knowledge about the decision making processes of Witmania to create an influence net. The net has one overall objective or target node: "Witmania stops its WMD program." From this target node, nodes representing various diplomatic efforts, surveillance flights, and psychological operations that can effect this decision along with their causal links are created. The influences of actions and perceptions of the leader of Witmania are also included. The intelligence analysts also include several military actions, including the use of a covert mission to destroy the WMD production facility, the use of a Unmanned Air Vehicle (UAV) as a diversion, and a neutral flight. The influence net models the reaction of the Witmania integrated air defense system (IADS) to the covert operation, UAV and neutral flights. The overall result is a large influence net created in SIAM with over 90 nodes, including 23 nodes for actionable events. Figure 8 is a thumbnail view of the structure of the influence net.

The intelligence analyst conducts a sensitivity analysis of the influence net to determine which controllable events have the greatest impact on the target node, stopping the WMD program. This analysis indicates that while diplomacy has some impact, the combined effects of the covert operation, UAV, and neutral flight significantly increase the likelihood that the WMD program will be stopped. As a result, it is decided to investigate combinations of these actions in more detail. Figure 9 shows a notional operational concept for the various courses of action under consideration.
Using the output file from SIAM and the conversion algorithm created in Design/CPN, the influence net is converted to a colored Petri Net. First, analysis of the sequences is conducted to eliminate any sequences that will not have the desired impact. Then the timing information is added to the best sequences to analyze the temporal aspects of the courses of action.

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<tr>
<th>Neutral Flight</th>
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<th>Covert Mission</th>
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It was decided to include the diplomatic events in all courses of action because these actions would take place prior to military action and may produce the desired results. The diplomatic efforts are composed of a sequence of four actions: Initial diplomatic efforts, surveillance flights, using the results of the surveillance flight to advertise the existence of the WMD program to the international community, and local psychological operations to influence public opinion against the WMD program. Figure 10 shows how the probability that the WMD program will be stopped increases from 26% to 48% as this sequence of diplomatic actions takes place.

Since the sensitivity analysis using SIAM indicated that the target node probability would increase significantly if a covert mission and UAV flight were conducted in conjunction with a neutral flight, the CPN model is executed using the complete set of 13 combinations of sequence of these actions shown in Table 1.

The control panel page of the CPN model has been set up to collect probability data on several intermediate nodes in addition to the target node. These include the probabilities that the Integrated Air Defense System (IADS) stands down due to the neutral flights, that the UAV survives, that the covert mission evades the IADS, and that the overall cover mission is a success. Figure 11 shows the results for the third sequence of Table 1: the neutral flight followed by the covert mission concurrently with the UAV. Similar charts are created for the 12 other sequences. The 13 charts show that the covert mission success dominates the outcome of the target node. The neutral flight increases the likelihood that IADS will stand down and the UAV has a 60% chance of survival. The overall conclusion is that the UAV provides little cover for the covert mission; covert mission success is independent of the UAV flight.

After reducing the number of candidate courses of action by analyzing the impact of the various sequences of actions, timing data including processes times for the various nodes in the net and starting times for the actionable events in the CPN model, is added to the model. For example, estimates of the time delays in passing information through the IADS and the time required for decisions to be made to stand down the IADS or have the IADS engage the covert and UAV missions are added to the appropriate nodes of the CPN. In addition, the planned time for the flight of the covert mission, the UAV and the neutral flight are incorporated in the tokens representing these events. The model is executed again for several combinations of these event times and data collected on the key nodes of the model.
The data collected indicate the time phased changes in probability of each event for which data was collected. Figure 12 shows an example to the changes in probabilities that the IADS will stand down due to the neutral flight and that the UAV will survive. Note that the advent of the neutral flight causes the probability of the IADS standing down to increase. As the UAV enters the IADS air space its probability of survival begins to decrease until approximately 25 minutes into the mission. Then there is a slight increase due to the interaction with the neutral flight. As the UAV mission lingers in the air space beyond 35 minutes, its probability of survival again decreases. This suggests that if the UAV is to be used, it should be kept in the IADS airspace for no more than 35 minutes. Other time histories of the probabilities of events are examined until the best time windows are determined.

5 Summary and Areas for Further Research

This work represents a successful integration of influence nets with discrete event models in a common environment. It is believed that this technology will allow a closer coupling between models designed to assess situations and compare potential courses of action, and dynamical models that can be used to provide detailed planning and evaluation of those courses of action.

To date we have not connected together any real operational models and influence nets in this common environment. Future research is planned to do this and develop guidelines and rules for constructing and interconnecting such models that is consistent with both the underlying mathematics of the models and the objectives of the enterprise. In addition, a sound methodology using the interconnected models for developing and evaluating courses of action based on measures of performance and measures of
effectiveness for the mission objectives needs to be developed. When fully established, this capability will enhance understanding of collaboration between teams of experts, each using tools and models appropriate to its discipline for situation assessment and course of action generation and evaluation.

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References

