Uncertainty Representations for a Vehicle-Borne IED Surveillance Problem

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Abstract—The aim of this paper is to detail further a Vehicle-Borne IED scenario proposed as an uncertainty modeling challenge to the information fusion community by the Evaluation of Techniques for Uncertainty Representation (ETUR) working group. This enrichment of the basic scenario is partly based on the careful comparison of formalizations published thus far by four uncertainty modeling experts as well as on the authors expertise in surveillance system design and risk assessment. The main additions reside in the exploitation of the temporal and spatial dimensions of the IED scenario initial statement. The authors show that the compromise between the expected risk, the time to certainty and time to intervene is central to the modeling of this very basic scenario and should be exploited further. According to the analysis of the formalizations of the VBIED scenario already published seems also of interest to introduce the notion of agents to clarify the definition of state spaces. From the proposed model elements the authors expect that the scenario can be extended for more practical uses by allowing the addition of historical datasets from which a priori knowledge can be extracted, measurements be made from maps, and available resources balanced against expected risk.

Keywords: Uncertainty Representation, IED, Evaluation, Surveillance, Evidence Theory.

I. INTRODUCTION

Since the introduction of alternative approaches to probabilities for representing and reasoning with uncertainty in the 60’s, analysis and comparing these different approaches has been an active research area. Indeed, the question is “What theory should I use to solve my problem”? Besides several (still current) debates between probabilities versus fuzzy set theory (e.g. [1]), other works maybe less dogmatic in spirit and adopting a constructivist point of view only aim at providing partial answers to this question while guiding the choice of the modeler toward one theory rather toward another depending on the context, nature of the data, etc. [2]–[6].

In 2011, the Evaluation of Techniques for Uncertainty Representation (ETUR) working group1 has been created as part of the International Society for Information Fusion. The goal of this group is to provide a forum to address the problem of the assessment and evaluation of the different Uncertainty Representation approaches developed so far. This includes classical approaches such as Bayesian probabilities, fuzzy sets, belief functions, possibilities, random sets, imprecise probabilities to name just a few.

In 2010, an Uncertainty Forum has been organized by Simon Maskell and John Lavery as part of the Information Fusion conference held in Edinburgh (UK) to provide a discussion on some different ways of representing and dealing with uncertainty using a common and single scenario as a reference point. As the authors of the Uncertainty Forum mentioned, “The goal of the Uncertainty Forum is not to come to specific conclusions about a linear or other ranking of approaches for representing uncertainty but rather to widen the spectrum of available options and link these options with situations in which they perform well”2. Prior to this forum, a Vehicle-Borne Improvised Explosive Device scenario had been submitted to 5 participants each aiming at the defense of one approach: Dezert-Smarandache Theory (Jean Dezert, [7]), human intelligence/processing (Peter Gill, [8]), Bayesian method (Simon Godsill), Dempster-Shafer Theory (Arnaud Martin, [9]) and the Transferable Belief Model (David Mercier, [10]).

This scenario has been recently selected as one of the 6 use cases within the ETUR working group, to serve the purpose of the group and explore the wide variety of available uncertainty representations. In particular, this includes considering (1) other approaches to uncertainty than the 5 already considered, as well as (2) alternative modelizations within the same theory. These URs are to be evaluated along a series of criteria defined within the Uncertainty Representation and Reasoning Evaluation Framework (URREF) ontology [11].

The selected use case (scenario) addresses a very recent and complex problem. According to the United Kingdom armed forces, an Improvised Explosive Device (IED) is: An explosive device, constructed using non-

1http://eturw.c4i.gmu.edu

2http://isif.org/fusion/proceedings/fusion2010/plenary-speakers.htm
Three key dimensions inherent in any surveillance problem are those of time, space and observations. Objects have spatial positions at a given time, and may change position at the next time step. Furthermore these objects, having physical substance, can be observed. Hence these notions should be, and are, even if not always explicit, part of the basic modelization of the scenario. The material world upon which all events occurs and all objects lie upon can be define as $S$, being a set of points defined over the product $(1, \ldots, M) \times (1, \ldots, N)$. The set of all observations $O$ is built upon $2^S$, that is, the set of all subsets of the space $S$.

A. **VBIED scenario**

We present here the VBIED scenario, in its original form, as proposed by the Uncertainty Forum:

- **Concern:** VBIED (Vehicle-Borne Improvised Explosive Device) attack on an administrative building $B$.

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3The text has been extracted from [7].

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- **Prior information:** We consider an Individual $A$ under surveillance due to previous unstable behaviour who drives customized white Toyota (WT) vehicle.
- **Observation done at time $t - 10$ min:** From a video sensor on road that leads to building $B$ 10 min ago, one has observed a white Toyota 200m from the building $B$ traveling in normal traffic flow toward building $B$. We consider the following two sources of information based on this video observation available at time $t - 10$ min:
  - Source 1: An Analyst $I$ with 10 years experience analyses the video and concludes that individual $A$ is now probably near building $B$.
  - Source 2: An Automatic Number Plate Recognition (ANPR) system analyzing same video outputs 30% probability that the vehicle is individual $A$’s white Toyota.

- **Observation done at time $t - 5$ min:** From a video sensor on road 15km from building $B$ 5 min ago one gets a video that indicates a white Toyota with some resemblance to individual $A$’s white Toyota. We consider the following third source of information based on this video observation available at time $t - 5$ min:
  - Source 3: An Analyst $2$ (new in post) analyses this video and concludes that it is improbable that individual $A$ is near building $B$.

Q1: Should building $B$ be evacuated?  
Q2: Is experience (Analyst 1) more valuable than physics (the ANPR system) combined with inexperience (Analyst 2)? How do we model that? 

**NOTE:** Deception (e.g. individual $A$ using different car, false number plates, etc.) and biasing (on the part of the analysts) are often a part of reality, but they are not part of this example.

**B. A multiagent decision problem**

The IED protection problem is by essence a multiple agent decision problem involving solutions similar to the ones proposed for critical infrastructure protection. A review of the methods used in this domain, in particular for the design, integration and optimization of early warning systems, one may refer to [13]. More specifically, the IED problem can be seen as a game between two players, one, called the attacker aiming at the destruction or disruption of assets critical to its opponent, the defender. While planning the attack, obtaining finance, recruiting, obtaining the material, building the IED, training, moving the IED, caching it, and eventually placing the IED at or near the targeted location, the attacker will be under constant surveillance from the defender and will thus avoid being caught by acting quickly and using several means of concealment. As depicted in [14] the attacker’s goals towards its target will be to minimize to risk of detection while maximizing speed of execution, generally favoring the minimization of detection if a conflict arises between the two objectives. The reader interested in recent works involving the modeling of such situations as multiagent systems will look into [15] and [16].
C. The surveillance system

The scenario described above is in fact part of a surveillance system such as the one described in [17] by Nickerson and Olariu. Figure 1 illustrates the surveillance system as a transition state system. Let us re-tell the story of the VBIED scenario in the context of a surveillance system as described in Figure 1. The story begins just after the detection step (D) (an individual is observed “due to previous unstable behaviour”). The scenario details then the monitoring state (M) involving indeed human attention. Here is where the uncertainty representation and reasoning take place. Agreeing that a total certainty will never be reached, what we expect of a uncertainty-based reasoning process is to come up to a conclusion with a level of certainty as high as possible in the smallest amount of time. The other crucial dimension is the reliability of the reasoning, i.e. its ability to provide correct identifications, or other said, its ability to maximize to correct identifications (true positives (TP)) while minimizing the wrong identifications (false positives (FP)).

In [17], the authors mention the trade-off underlying a surveillance problem between the time to certainty $T_c$, and the time to intervention, $T_i$. Indeed, we can expect that the more the information can be gathered, the more certain we will be about the event under surveillance, but however, the less the remaining amount of time to intervene will be. The intervention time here is understood as both the time to come up to a decision and to perform the intervention as such. Obviously, the sum of these two times must be lower than the time needed by the malicious individual to reach his target, $T_t$ (time to target):

$$T_c + T_i < T_t$$

Surveillance systems are thus designed such that the selection of the decision point DP balances the level of uncertainty against the cumulative cost resulting from delayed intervention. Figure 2 illustrates the trade-off between the certainty (in blue) and the cost of intervention (in red). The cumulative cost and the uncertainty are represented as time functions parameterized by the time instant corresponding to DP. DP1 in Fig. 2 leads to a cumulative cost that increases less than with that obtained with DP2 at the expense, however, of higher level of certainty. Poor information generates false alarms whose consequences have to be balanced against the benefits gained with true alarms.

D. Integrating a risk model

As introduced just above (through the notion of cost), another important part is the risk associated with the decision to be taken. We can for instance consider the following qualitative model (the $\times$ symbols, rather means being function of than multiply):

$$\text{Risk} = \text{Consequence} \times \text{Vulnerability} \times \text{Threat}$$

The risk here, although there are several interpretations, can be understood as being the expected cost of loosing a valuable asset given an attack. The consequence is measured in terms of value, that is the value of the loosing the asset, in part or all of it. The vulnerability is the probability or likelihood of succumbing to the attack. Here one could define several vulnerability measures given different types of attacks, or given the context of the attack. The threat is the probability or likelihood of being attacked. This can be based on historical records of similar types of attacks, declarations of intents, simulations, opinions from experts, etc. For our modeling purposes we need to recall that in practice some form of a priori knowledge is required to fully model risk, and that often several types of threats must be taken into account in decision making under the stress of risk.
For our scenario this means offering the possibility to plug database management systems to the surveillance system and considering other types of vehicles since blast power and range largely depends on the size of the vehicle carrying the IED.

Now the elements of a VBIED surveillance problem have been mentioned; we will in the following section address the modelization task of the VBIED scenario at hand, and show how these elements can be integrated and considered.

III. ELEMENTS OF MODELIZATION

The purpose of the VBIED scenario as originally defined for the Fusion 2010 Uncertainty Forum and as selected for the ETUR working group, is to act as a reference problem, with fixed inputs and outputs, in which different uncertainty representations can be compared and assessed according to some criteria [11]. We would like in this section highlight the impact of the basic modelization, and show how several solutions to the same problem can be drawn by different modellers, simply because the problem modelization is a very personal task with some part of subjectivity. Thus, a common scenario (together with defined criteria for evaluation) can serve two purposes: (1) For a given fixed framework, analysis of the wide variety of the modelizations available, (2) for a fixed basic model, comparison of different frameworks. To our opinion, the Uncertainty Forum reached the two objectives: (1) with the three “evidence-like” theories (evidence, TBM and DSmT) and (2) with one the of the previous three and the two others approaches (probabilities and the human factor analysis).

A. Existing modelizations

Let us denote by $A$ “the suspect individual”, by $B$ “the building”, by $WT$ “$A$’s white Toyota”. Table I summarizes the existing modelizations of the VBIED problem, considering only what we call the “evidence-like” theories that are evidence theory itself (DST, for Dempster-Shafer Theory) [18], [19], the Transferable Belief Model [20], Dezert-Smarandache Theory (DSmT) [21] and Referee Functions (RF) [22]. For an easier comparison of the modelizations proposed, we unified the notations and minimized the number of symbols used. Note that in a separate publication [23], Dezert and Smarandache provided a very detailed analysis with several variations of the modelizations. We selected in Table I only the basic ones.

For the problem modelization, a series of personal choices need to be made:

1) Definition of the frame(s) of discernment: This is the first and more crucial step as all the upcoming modelization will rely on it. At this step, the relevant elements of the problem are identified, the set of possible states of the worlds are considered. For instance, Martin and Mercier take for granted that $A$ is driving $WT$ while Dezert and Dambreville consider the possibility that $A$ may not be in his vehicle $WT$. Martin considers that $A$ may be not dangerous, while this eventuality is neglected by the others. Dezert considers frames with ambiguous meanings, $\Theta_A$ and $\Theta_V$ seem to rather refer to agents $A$ and $WT$ than states, while $\Theta_B$ refers to a predicate to be applied to a given object. For instance, the proposition $(A, V, B) \cup (A, V, \overline{B})$ (denoted as $(A, V)$ in Table I) means both “$A$ is in $WT$” and “$V$ is $A$’s white Toyota” (see $m_2$). Dambreville modified slightly the meanings of the singletons to fix this issue. The number of possible states considered varies then between 2 and 8.

2) Selection of sources (or pieces) of information to be further combined: Besides the three sources (the two experts and the ANPR) some authors consider prior information about the dangerousness of $A$ (Martin) or about the fact that $A$ may not drive his vehicle (Dezert).

3) Modelization of other elements of quality of information like reliability of the sources in this case (but it could be aspects of relevance for instance): Reliability has been modeled using a discounting factor by all the authors (except Mercier). Some numerical values have been assigned (Dezert, Dambreville), or just a ranking has been considered (Martin).

4) The definitions of the belief functions (or Basic Probability Assignments) as such: All the authors agreed on the modelization of the ANPR piece of information as a probability function and to model the experts’ opinion as belief functions. While the probability is not ambiguous, we observe some differences in the initial BPAs proposed for the two human experts. Although a finer assessment of the consequences of such choices on the final result would be interesting, it is out of the scope of the present paper and will be done in future works.

5) The choice of the fusion (combination) rule: Here, different rules of combinations and be compared and the modeler can then eventually advocate for one rather than an other on some given criterion. This criterion can be purely subjective (the rule leads to counter-intuitive results) or objective (this rule provides better classification rates).

6) The choice of the decision rule: All the authors considered the decision at a classification level, that is “Is $A$ near $B$” and translated their answer to Question 1. In other words, if “$A$ is near $B$”,

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then Evacuate. Dezert and Dambreville considered several levels of threats, based on their finer modelizations (e.g., A may be near B without V). Only Mercier, through the TBM addressed directly the question of the evacuation of building B, and provided a decision rule in which the cost of evacuation is considered.

From these modelizations, we observed that:

- The notion of time has not been exploited. For instance, from the scenario we know that the white Toyota observed at t-10 min. is "traveling in normal traffic".
- The notion of space is not exploited. Only two spatial positions (200m and 15km from B are considered).
- The decision theory involving risk (or cost) has been only considered by Mercier within the TBM framework.
- The state space definition is not totally clear as are the meaning of the propositions (Dezert and Dambreville).

In the following section, we propose a general model which could help in considering all these aspects together while being consistent with the modelizations already proposed.

B. A multi-agent model for extensions to the original scenario

We consider a set of agents $\mathcal{A} = \{a_{10\text{years}}, a_{\text{ANPR}}, a_{\text{new}}, a_{\text{DM}}, e\}$; $a_{10\text{years}}$ is the experienced human agent with 10 years of experience, $a_{\text{ANPR}}$ is the Automatic Plate Number Recognition system agent and $a_{\text{new}}$ is the new in post human agent. $a_{\text{DM}}$ is the human decision maker agent who will eventually make the decision to evacuate the building. $e$ denotes the environment agent and represents all the activity on which we have no control.

We consider the agents’ model put forward in [25] and derived from the seminal work of [26]. An agent $i \in \mathcal{A}$ has a local state $l_i$, encoding all the information it has access to, a set of possible actions $a_i$ that it can perform and a protocol (strategy) $P_i$ mapping local states to actions. Although not necessary, it could be convenient to further detail the local state $l_i$ as a tuple of the form:

$$(\text{data}_i, \text{alg}_i, \text{Bel}_i)$$

where $\text{data}_i$ contains data representing background knowledge of $i$ (maps, databases, etc) but also the series of observations (the pictures extracted from the videos in this case) to be processed by alg$_i$, an algorithm for truth evaluation alg$_i$ of some propositions of interest ("A
is near \(B\) for instance), and \(\text{Bel}_i\) is a belief function\(^4\) representing \(i\)'s uncertainty and output by \(\text{alg}_i\). Note that a binary output for \(\text{alg}_i\) is only a special case where the agent is certain about his statement.

Each of the three human agents has as possible states either a belief that \(A\) is near \(B\) or a belief that \(A\) is far from \(B\). The possible actions for \(a_{10\text{ years}}\), \(a_{\text{ANPR}}\), \(a_{\text{new}}\) are only a test action whose purpose is to evaluate truth values of propositions of interest by means of their \(\text{alg}_i\), using their data, and based on their recent observation through Video 1 or 2.

The ANPR system has in its local state \(WTA\)'s real plate number\(^5\) as well as \(WTA\)'s estimated plate number. Although not detailed, the ANPR's algorithm compares the observed \(WTA\)'s plate number with \(WTA\)'s plate number (assumed to have been previously correctly identified). This automatic agent provides an objective judgment with numerical assessment, that is “there is 30 \% of probability that \(WTA\) is \(WTA\)'s plate number. The ANPR's algorithm involves several steps of image processing (plate localization, orientation and sizing, normalization, character recognition) followed by an Optical Character Recognition (OCR) algorithm and a syntactical analysis to be correlated with countries' specific rules.

The last step of the process is then to compare the estimated plate of \(WTA\) with the known plate of \(WTA\). The binary comparison of each pair of digits could lead then to having 2 correct digit over 6, hence a probability of 0.33.

The decision maker agent \(a_{\text{DM}}\) has in his local state the three other agents’ statement about “\(A\) is near \(B\)” and evaluates the truth value of that proposition based on 1, 2 or 3 of them (test action), basically by aggregating their 3 beliefs. Moreover, he is able to decide to evacuate the building, evacuate. This decision should be taken considering costs of evacuation, and the risk model as it has been introduced in Section II-D and used by Mercier.

The environment can be modeled with several entities and states of interest, in short the possible states of the world, the frames of discernment. In this particular case, it is composed minimally of the suspect individual \(A\) under surveillance whose behavior has been judged unstable previously, its White Toyota \(WT\) which is observed through two videos. Globally, the environment is supposed to behave according to an unknown strategy \(P_e\) that the surveillance system is expected to estimate and predict.

In their respective modelization, Mercier, Martin and Dezert consider either 2, 4 or 8 possible states for the environment, as illustrated in Figure 3. For Mercier, no uncertainty is linked to the dangerousness of \(A\) and the eventuality that \(A\) may not be in \(WTA\) is not considered. Provided the information given in the scenario and the available perception means described, this is the more faithful modelization. Martin while not questioning the possibility for \(A\) not being in his car, considers however the eventuality that \(A\) may not be dangerous hence 4 possible states. The dangerousness of \(A\) may indeed have an impact on the risk analysis and thus on the decision to evacuate or not the building. However, as actually stated in the original version of the scenario, no information can be drawn about the dangerousness of \(A\).

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Several propositions of interest can be derived such as: \(\phi_1 = \text{WT} \text{ is near } B\), which truth\(^6\) set is \(\{s_5, s_6, s_7, s_8\}\); \(\phi_2 = A\) is dangerous, which truth set is \(\{s_1, s_2, s_5, s_6\}\); \(\phi_3 = A\) is in \(\text{WT}\) which truth set is \(\{s_2, s_4, s_5, s_7\}\); etc.

Figure 3 illustrates different granularities for the problem. However, the access to the finest one is conditioned by the availability of corresponding perception means. Indeed, if no video is able to identify \(A\) itself without his vehicle, then the finest-grained partition of the model will not be accessible.

\(\text{C. Extensions}\)

Provided the different model elements described above, several extensions to the scenario can be considered:

\(^4\)This representation has been chosen for setting the ideas, but other uncertainty representations can be considered instead.

\(^5\)\(WTA\) denotes here \(A\)'s white Toyota to distinguish from any other white Toyota \(WT\), for instance the one observed by Video 1 and 2.

\(^6\)The truth set of a proposition is the set of all possible states in which this proposition is true.
1) Extension along the agents: Having more than 3 agents, mixing human and synthetic agents, and thus increasing the number and nature of pieces of information to be processed. For instance, some vague predicates could be introduced.

2) Extension along the agents’ local states: Allowing the agents to have more data in their local states, such as for instance, maps of past IED events for the area under surveillance. Also, an OCR database may be added to the ANPR agent, together with a vehicle database. The information extracted from the databases would either be integrated in the ANPR’s identification algorithm (e.g. weighting of score labels probabilities by class priors). Moreover, maps of past events together with the associated database could be attached to any of the human agent. Such a database is a list of IED events, with a series of attributes including the space location, the time, the delivery system (vehicle-borne, person-borne, passive, directional, placed), the initiation mode (timed, command-initiated, victim-operated) [12]. These databases would become then prior sources of knowledge for the expert agents which, combined to the observations, would contribute to the evaluation of the truth of “A is near B”.

3) Increasing the propositional language for the agents allowing other propositions than only “A is near B”. For instance, “Is A’s vehicle a large vehicle?”, etc.

4) Extension along the time: Considering a series of observations for different time steps.

5) Extension of the environment’s model: Considering two distinct entities for A and WT (as Dezert proposed) rather than a single one is already an extension. But this can be further extended to a large number of individuals A1, . . . , An, other vehicles, etc. Besides, we can consider other possible states for the environment. Indeed, the number of possible states may be further increased along two dimensions: (1) Reducing the granularity by extending binary states to multi-valued states, ordered or non-ordered. For instance, extending “near B” and “far from B” to “at 20km from B”, “at 15km from B”, . . . , “at 10m from B”. The same can be done for the state D considering a series of dangerousness (crisp) states; (2) Increasing the kinds of states like for instance, besides considering “near B” and “dangerous”, we can also consider “badly intended” or “in WT A” for A, or “holding a bomb” or “stuck in traffic” for WT. Also, we can consider a 2-dimensional spatial description rather a single one. As mentioned in Section II, space is a crucial dimension of a surveillance problem. Indeed, spatial references allow to compute distances (A to B, for instance), evaluate speeds, and evaluate vulnerability. Note that as mentioned above, every state-related extension must be supported by corresponding perception means, memory capacities, or other source of knowledge.

Finally, as possible extensions, considering other scenarios together with their associated datasets (such as the use cases identified in the ETUR working group) could be of interest as far as the complexity of the scenario and the traceability of the uncertainty is concerned. For instance, the “unstable behavior” of A could have been issued from a crowd analysis system (cf. Crowd analysis use case), the ANPR system could be coupled with a vehicle identification system (cf. vehicle identification use case), several videos can be considered to track A (cf. image fusion and tracking use case), some asymmetric threat detection system can provide prior information (cf. Asymmetric threat detection use case).

IV. CONCLUSIONS AND FUTURE WORKS

We analysed and detailed a Vehicle-Borne Improvised Explosive Device scenario for the purpose of uncertainty representations evaluation. We showed that this apparently simple scenario addresses a very complex problem of surveillance involving implicitly elements such as risk, vulnerability, multi-agent systems, decision theory, and that the notions of time and space cannot be neglected. Based on some observations of the former modelizations proposed, we highlighted the interest of basic modelization general enough to encompass for the previous notions as well as for a clear definition of state spaces, frames of discernment and proposition of interest. We finally propose some possible extensions of this scenario including existing datasets and building links with other scenarios. In the future, we will further formalize the basic modelization and extensions and will compare several uncertainty representations on this basis. Although not explicitly shown here, we aim at demonstrating the interest of a modelization relying on a clear semantics for complex high-level information fusion problems involving human decision-making.

REFERENCES