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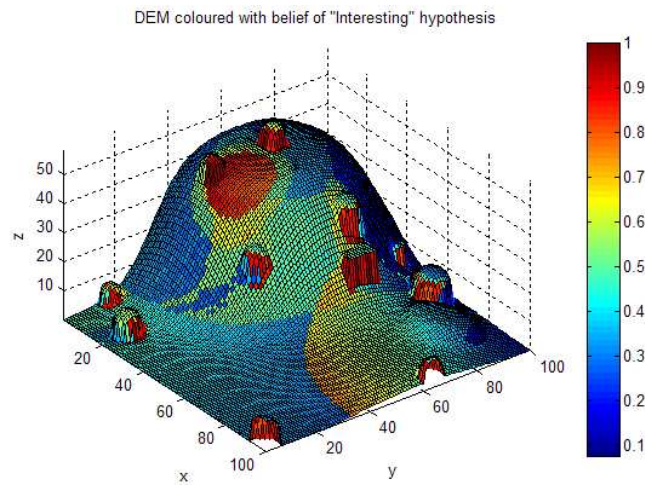
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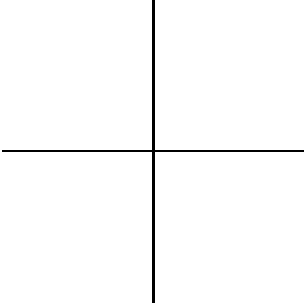
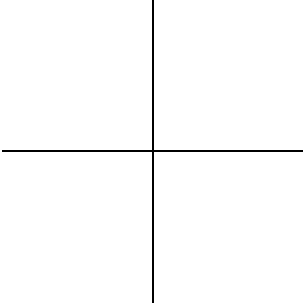
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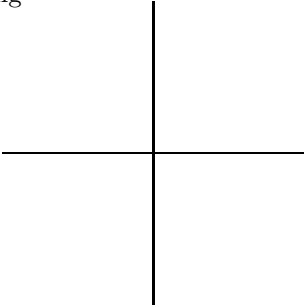
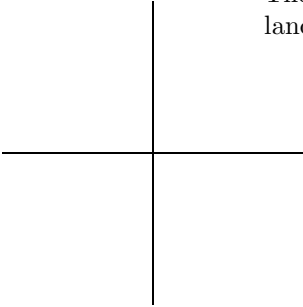
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About the cover: This figure is drawn from Chapter 1 and corresponds to the 3D simulated interest map for automatic goal allocation for a planetary rover. The colors are associated to the interest level for each point on the surrounding landscape.

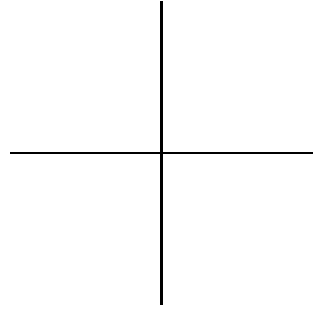
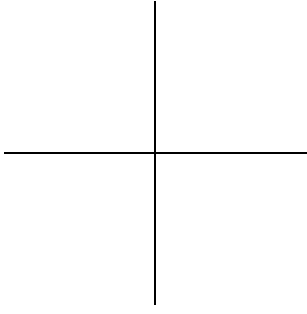




# Contents

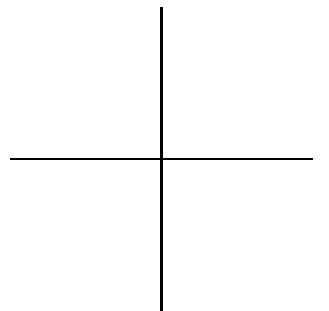
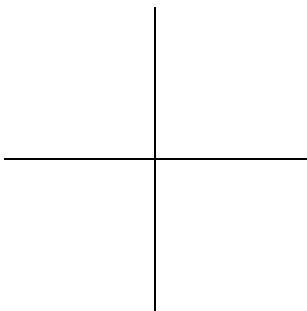
<b>Part I</b>	<b>Advances on DSMT</b>	<b>1</b>
<b>Part II</b>	<b>Applications of DSMT</b>	<b>3</b>
<b>Chapter 1</b>	<b>Automatic Goal Allocation for a Planetary Rover with DSMT</b>	<b>5</b>
	<i>by Massimiliano Vasile and Matteo Ceriotti</i>	
1.1	Introduction . . . . .	6
1.2	Plausible and Paradoxical Reasoning . . . . .	9
1.3	Modelling Interest for a Planetary Rover . . . . .	10
1.3.1	Modelling of sensor information . . . . .	10
1.3.2	Definition of the Interest Map . . . . .	11
1.4	Some Results with DSMT . . . . .	16
1.4.1	DST applied the generation of the Interest Map . . . . .	23
1.5	Final Remarks . . . . .	29
1.6	Acknowledgments . . . . .	29
1.7	References . . . . .	30
	<b>Biographies of contributors</b>	<b>33</b>



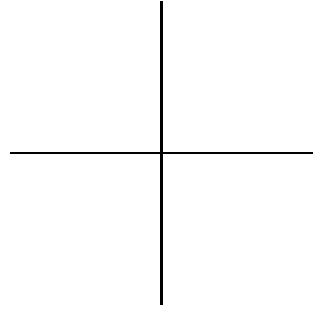
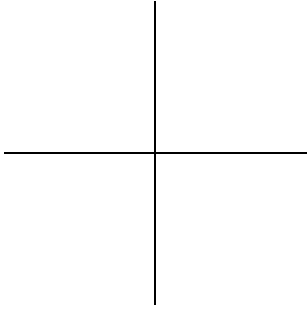


Part I

Advances on DSmT

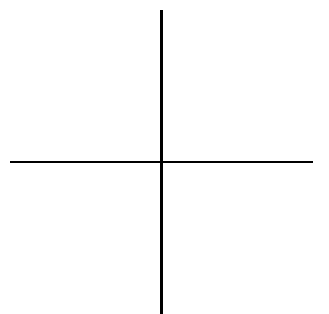
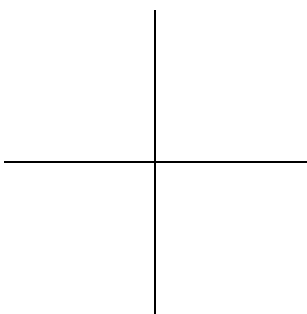






## Part II

# Applications of DSMT









## Chapter 1

# Automatic Goal Allocation for a Planetary Rover with DSmT

Massimiliano Vasile, Matteo Ceriotti  
Department of Aerospace Engineering,  
University of Glasgow,  
James Watt South Building,  
G12 8QQ, Glasgow, UK  
m.vasile@aero.gla.ac.uk, m.ceriotti@aero.gla.ac.uk

**Abstract:** *In this chapter, we propose an approach for assigning an interest level to the goals of a planetary rover. Assigning an interest level to goals, allows the rover to autonomously transform and reallocate the goals. The interest level is defined by data-fusing payload and navigation information. The fusion yields an “interest map”, that quantifies the level of interest of each area around the rover. In this way the planner can choose the most interesting scientific objectives to be analysed, with limited human intervention, and reallocates its goals autonomously. The Dezert-Smarandache Theory of Plausible and Paradoxical Reasoning was used for information fusion: this theory allows dealing with vague and conflicting data. In particular, it allows us to directly model the behaviour of the scientists that have to evaluate the relevance of a particular set of goals. This chapter shows an application of the proposed approach to the generation of a reliable interest map.*

## 1.1 Introduction

Based on the experience gathered with past Mars robotic missions, a number of future space missions envisage the use of robots for the exploration of distant planets [1]. All of them have strong scientific requirements but the poor knowledge of the environment where the robots will operate, makes the definition of specific goals dependent on contingent events and observations. If the allocation the goals is performed entirely on the ground, the robot will have to wait for new instructions every time a new, unforeseen event occurs or a new set of scientific data is available.

Therefore, it would be desirable to have an autonomous system able to make decisions not only on how to reach a given set of goals but also on which mission goals to select. Furthermore, the persistency of a mission goal may lead the system to repeatedly re-plan in order to meet the goal though the goal is unreachable or has lost its original importance. Goal transformation or goal reallocation is an important feature required in dynamic and rapidly changing environments but can become extremely important also in poorly known environments or when exploration and discovery are the main drivers of a mission [2]. For example, assume that, for a mission to Mars, a set of observations from space is used to define a set of goals for a planetary rover. During the mission, however, the rover may find that the goals are unreachable (e.g. if the goal was to collect a sample of a specific rock, the rock could be unreachable) or not interesting anymore (e.g. a different rock may display more interesting features). Then, the ground control team, together with the scientific community, would have to decide what to do. While the ground control team is devising a new plan and a new set of goals the rover would remain idle waiting for instructions. In order to avoid this waiting time, the idea is to adjust mission goals of the planner in addition to the adjustment of the plans themselves. Previous works on goal transformation addressed terrestrial or military applications [2, 3], and did not include the scientific data coming from the payload in the reallocation process.

In this work, we propose the autonomous generation or reallocation of given mission goals in order to maximise mission return. The aim is to have the most rewarding sequence of goals or the addition, deletion, modification of goals depending on contingent events or discoveries. Payload information is integrated in the planning process in order to make the rover mimicking the behaviour of scientists. Goals are generated, modified or reallocated in order to maximise the overall scientific return of the mission. A family of plans is then generated for each set of ordered goals and the most reliable feasible plan of the most interesting set of goals is executed. Reliability is taken into account, together with interest, in the process of choosing the plan to be executed [4]. The

planner and the goal transformation algorithm are part of a multi-layer autonomous system called Wisdom. The Wisdom system is a non-deterministic, deliberative-reactive system for rover autonomy in harsh, unknown environments. The system was developed and implemented on a six wheeled prototype rover (named Nausicaa) at Politecnico di Milano, as part of a study, supported by the European Space Agency, for the development of advanced systems for space autonomy [5].

In this chapter, we present specifically the approach used in Wisdom to generate an interest value through the data fusion of navigation and payload data for an autonomous planetary rover. The definition of an interest value avoids wild goal sequences for which only an empty set of actions is feasible (a plan with no steps), since only goals that are interesting for the mission can be generated or transformed. In Wisdom, goals are extracted from a pool of high level conceptual directives and are organised into a sequence by using the STRIPS paradigm for planning [6]. Briefly, goals are distributed in a logical sequence from an initial goal to a final one with preconditions and post-conditions, but are not scheduled unless the time is explicitly part of a goal (e.g. reach a given location in a given time). The sequence can be adjusted during execution and is qualified according to the total level of interest of all the goals. The definition of a pool of high level directives limits the set of goals to those for which the autonomous system was designed but avoids the persistency of unreachable goals.

Previous attempts to model vague concepts such as interest or curiosity for autonomous agents can be found in the work of Schmidhuber [7], who proposed the use of a co-evolutionary algorithm to evolve curiosity in an artificial intelligence system. In this case, however, there is no specific use of instruments or any mission-specific measurements or data to support the decision-making process. Instead, in this chapter, a full exploitation of scientific data is proposed in order to build an interest map of the surroundings. Pieces of scientific data from different sources are fused with navigation one to yield a single value for each point on the map. The map, then, evolves during the mission depending on the available observations.

In general terms, data fusion is the use of independent and/or redundant ancillary data from various sources to improve the data already available. Wald formally defined data fusion as: “A formal framework in which are expressed the means and tools for the alliance of data originating from different sources. It aims at obtaining information of greater quality” [8]. Here we understand data fusion as a way to combined information from different sources in order to obtain a single unambiguous value, useful to make decisions on the interest of a particular set of goals.

The combination of scientific and navigation data requires the fusion of pieces of information coming from physically different sensors. Each sensor measures a different parameter, has its own characteristics, reliability and uncertainty on measurements. Moreover, if each instrument is interpreted as a scientist expressing an opinion, we can associate to each data set an interest level with associated uncertainty. This would mimic the process performed on ground when a new set of scientific data is available. The data fusion process is then required to collect all the different pieces of information, with associated uncertainty, and combine them together [9].

In order to fuse data from the sensors and find the most interesting areas of the surrounding environment, the Dezert-Smarandache theory of plausible and paradoxical reasoning [10] was used. This theory has been successfully applied to many engineering problems, like the estimation of behaviour tendencies of a target [11], or the prediction of the land cover change [12]. In those works, it was proven that this modern theory overcomes the limitations of both fuzzy logic and evidence theory.

The main advantage of the paradoxical reasoning is that it allows dealing simultaneously with uncertain and paradoxical data from different, providing a solution even in the case of conflicting information. A conflict leads to a non-decidable situation that would put the rover into idle mode, waiting for instructions. The conflict could arise when different sources (different instruments) are assigning opposite interest values to the same area or when the navigation expert suggests avoiding an area that has a high level of interest. Conflicts on the ground would be resolved through a discussion among the scientists and the mission control team, leading to a new set of goals. An autonomous resolution of conflicts by the rover, would reduce the time spent to wait for instructions from the ground station.

In this chapter, after a brief introduction to the theory of Plausible and Paradoxical Reasoning, the application to modelling interest for the Wisdom system is explained. The way of modelling interest fusing information from different sensors is described, and an application to a synthetic environment is shown. At the end, we will present a brief discussion about the possible use of Dempster-Shafer theory for the assignment of an interest. It should be noted that the key point of this work is not to propose a new theory of information fusion or to present the advantages of one theory over another. The key point is to propose an innovative way to assign a value of interest to mission goals for a planetary rover so that the goals can be autonomously adapted to contingent mission events.

## 1.2 Plausible and Paradoxical Reasoning

The theory of plausible and paradoxical reasoning (or Dezert-Smarandache theory, DSmT [10]) is a generalisation of the Dempster-Shafer evidence theory [13], which is in turn a generalisation of the classical probability. The foundation of the DSmT is to abandon the rigid models of the previous theories, because for some fusion problems it is impossible to define or characterise the problem in terms of well-defined and precise and exclusive elements.

Given an experiment, the frame of discernment  $\Theta = \{\theta_1, \theta_2, \dots, \theta_n\}$  is the set of all possible events. The model on which the DSmT is based allows dealing with imprecise (or vague) notions and concepts between elements  $\theta_i$  of the frame of discernment  $\Theta$ . The DSmT includes the possibility to deal with evidences arising from different sources of information which do not have access to absolute interpretation of the elements  $\theta_i$  under consideration. This means that some events may also be overlapped and/or not well defined.

If  $\Theta$  is the frame of discernment, we can define the space  $D^\Theta$ , called hyper-power set [14], as follows:

1.  $\emptyset, \theta_1, \dots, \theta_n \in D^\Theta$ ;
2.  $\forall A, B \in D^\Theta, (A \cup B) \in D^\Theta, (A \cap B) \in D^\Theta$ ;
3. No other elements belong to  $D^\Theta$ , except those obtained by using rules 1 and 2.

Once  $D^\Theta$  is defined, we can apply the map  $m(\cdot) : D^\Theta \rightarrow [0, 1]$ , called *general basic belief number*, or gbba [10], such that:

$$\begin{aligned} m(\emptyset) &= 0, \\ \sum_{A \in D^\Theta} m(A) &= 1. \end{aligned} \tag{1.1}$$

A set of gbba, referred to the same frame of discernment  $\Theta$ , is called evidence. This approach allows us to model any source that supports paradoxical (or intrinsically conflicting) information. The theory of Dezert-Smarandache defines a rule of combination for intrinsically conflicting and/or uncertain independent sources. If two experts give their opinions in terms of bodies of evidence  $m_1$  and  $m_2$ , their combination is given by:

$$m_{12}(A) = \sum_{\substack{B, C \in D^\Theta \\ B \cap C = A}} m_1(B)m_2(C), \forall A \in D^\Theta. \tag{1.2}$$

Note that this rule is commutative and associative and requires no normalisation procedure. Moreover, it can manage the paradoxical information without any other assumption, thus overtaking some limitations of other probability theories - like the evidence theory - in which the frame of discernment shall be based on a set of exhaustive and exclusive elements. All the pieces of evidence in Eq. 1.2 are then used to give two uncertainty values, the belief and the plausibility:

$$\begin{aligned} Bel(A) &= \sum_{B \in D^\Theta | B \subseteq A} m(B); \\ Pl(A) &= \sum_{B \in D^\Theta | B \cap A \neq \emptyset} m(B). \end{aligned} \quad (1.3)$$

The belief of an event A is the sum of all the prepositions that totally agree with event A, while plausibility sums up all the prepositions that agree with A totally or partially. An estimation through classical probability theory would fall in the interval defined by the values of belief and plausibility.

### 1.3 Modelling Interest for a Planetary Rover

The high level of autonomy required to a planetary rover demands for the ability to choose the mission goals, without human intervention, once high level mission objectives are defined, in order to maximise the scientific return of the mission. These objectives, such as “look for water” or “look for traces of life”, do not identify exactly where to go and which experiments to perform. The rover should be able to uniquely define what is interesting, by means of the information gathered during the mission, and make decisions without waiting for instructions from the ground station. The collected pieces of information can be incomplete and uncertain. In particular, the Wisdom system uses different sensors to obtain the pieces of evidence required to make a decision. Each instrument plays the role of a scientist or of a ground control specialist. DSMT is used to model the following situation: each scientist (or specialist) expresses an opinion on the interest of a given object or portion of the surrounding area; the scientist admits no uncertainty but the one that comes from the instruments. On the other hand, every scientist leaves some margin for discussion, accepting the existence of opposite opinions.

#### 1.3.1 Modelling of sensor information

Nausicaa, the rover used to test the Wisdom system, is equipped with an infrared camera (the scientific payload) and two optical navigation cameras

that give a stereographic view of the surrounding environment (the navigation module). The optical stereo images are used to generate an elevation map of the ground, called Digital Elevation Map or DEM. The DEM is a matrix containing the height of the corresponding point on the ground. The DEM can be a partial reconstruction of the surroundings. Some parts of the terrain may not be in sight, because hidden by other parts (e.g. rocks or hills), and thus it is not possible to have any information about them. Furthermore, the algorithm can fail to determine the height of some points, especially if the image quality is poor. For these reasons, a second matrix is stored together with the DEM: it contains the uncertainty on the elevation of each point in the DEM. Values are between 0 and 1, where the former means total certainty on the elevation. Besides giving information on the elevation of the ground, optical images provide information on the texture of objects and surfaces. A texture map is then created by associating to each point in view an integer value identifying a specific material. Since this information might not be accurate or the image could be poor, a map of uncertainty is associated to the texture map. The payload mounted on Nausicaa generates a thermal map of the environment. This map is analogous to the DEM, but contains the temperature of each visible point. An uncertainty map is then associated to the thermal map, in order to take into account partial information due to occultation or the measurement noise of the infrared sensor. The final step consists of fusing the data of the three maps, to generate a single one: the interest map.

### 1.3.2 Definition of the Interest Map

The interest map is a matrix in which each element represents the belief that a particular spot on the ground is interesting. A frame of discernment  $\Theta = \{I, NI\}$  was defined, where  $I$  is the hypothesis *interesting* and  $NI$  is the hypothesis *not-interesting*. Interest is a vague concept and is subjective in nature. The associated hyper-power set is defined as  $D^\Theta = \{\emptyset, I, NI, I \cup NI, I \cap NI\}$ , and gbbas are assigned to the interesting and not interesting hypotheses, but also to:

- $I \cup NI$ : uncertain hypothesis. Represents the amount of ignorance, or the lack of knowledge of the expert which is dealing with the gbbas assignment. The expert assigns evidence to this hypothesis when the uncertainty on the data is high, due for example to distance, error on the sensor, or even lack of data.
- $I \cap NI$ : paradoxical hypothesis. This is the case in which two distinct scientists disagree on the interest level of a particular area. One of the scientists, according to the readings of his instruments, assigns a very



high gbba to the interesting hypothesis while the other assigns a very high gbba to the not interesting hypothesis.

Note that in the classical probability theory, these two additional hypotheses do not exist. Furthermore, the difference between the uncertain and the paradoxical cases is that the former expresses uncertainty due to lack of knowledge or information, while the latter does not claim any ignorance, but the possibility that both hypotheses could be true at the same time.

As a consequence, the two associated hypotheses are vague, can be overlapped, and can not be considered as mutually exclusive. The various pieces of information can be conflicting and highly uncertain. These types of information can be effectively handled through DSMT since it can manage conflicts among various experts and provides a single rule of combination.

The interest map is created point by point (see Fig. 1.2), by fusing all the available pieces of information (or evidence that a point is interesting or not) about each one of the maps as summarised in Fig. 1.1.

A set of independent experts (the instruments) creates the bodies of evidence that will be fused. For each point on the map the expert has to express an opinion on whether the point is interesting or not based on some evidence. The opinion is expressed by assigning gbba to each point on the map. The evidence comes from the readings of the navigation and scientific instruments. In particular, three experts were created, one for each map. The gbba that each expert assigns to a point on the map depends on the scientific objectives of the mission and on the available measurements. The measured values are compared against the values in a reference look-up table (the tables for the three experts can be found in Table 1.1 to Table 1.3). For example, in this work, we assume that the expert associated to the DEM is interested in sharp edges and in the lateral surface of the rocks since they are easily accessible. Thus, it assigns much gbba to the interesting case and little to the not interesting case, when the value of the gradient of the DEM is high, and vice-versa (Table 1.1). In addition, for some values of the gradient, gbba is also assigned to the paradoxical case. This is done not because of lack of knowledge of the roughness of the terrain (in which case, gbba is assigned to the uncertain hypothesis), but because the value of the gradient alone would not be sufficient to completely define whether an area is interesting or not. Assigning gbba to the paradoxical case allows for the integration of the opinions of other experts even if they are conflicting with the one of the DEM expert.

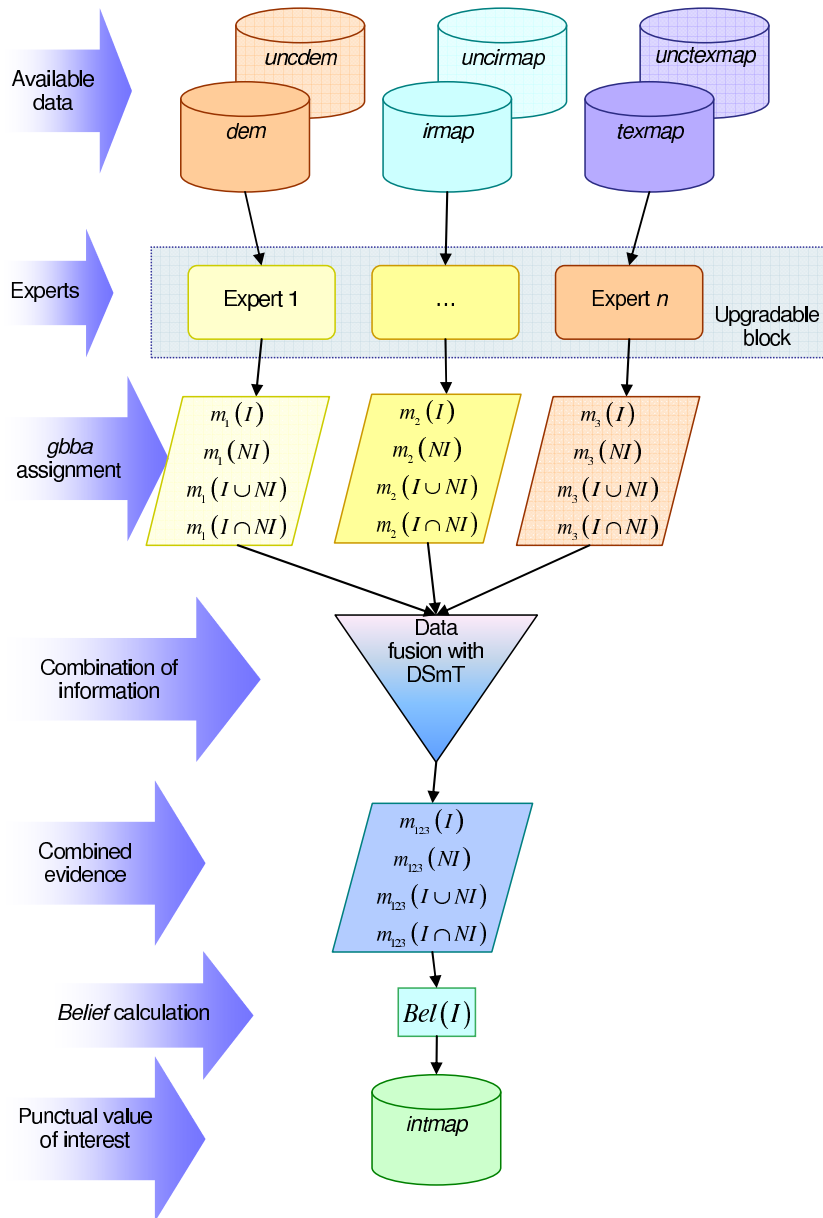


Figure 1.1: Diagram of the procedure to create the interest map.

In the same way, the temperature expert assigns interest to some temperatures (Table 1.2), and the texture expert assigns interest to some specific textures (Table 1.3). Non-dimensional units have been used in these tables. As before, gbba is assigned to the paradoxical hypothesis when the values associated to temperature and texture cannot be used to completely establish whether the point is interesting or not.

Modulus of the gradient of the DEM	$m(I \cap NI)$	$m(NI)$	$m(I)$
[0, 1)	0.20	0.80	0
[1, 3)	0.30	0.60	0.10
[3, 5)	0.10	0.10	0.80
[5, 7)	0.15	0.05	0.80
[7, 9)	0.05	0.05	0.90
[9, $+\infty$ )	0.05	0	0.95

Table 1.1: Table for the DEM expert.

Temperature	$m(I \cap NI)$	$m(NI)$	$m(I)$
[0, 20)	0.20	0.80	0
[20, 40)	0.40	0.50	0.10
[40, 60)	0.05	0	0.95
[60, 80)	0.15	0.05	0.80
[80, 100)	0.05	0.05	0.90

Table 1.2: Table for the temperature map expert.

Texture	$m(I \cap NI)$	$m(NI)$	$m(I)$
Texture not in database	0.20	0.80	0
1	0.30	0.60	0.10
2	0.10	0.10	0.80
3	0.15	0.05	0.80
4	0.05	0	0.95

Table 1.3: Table for the texture expert.

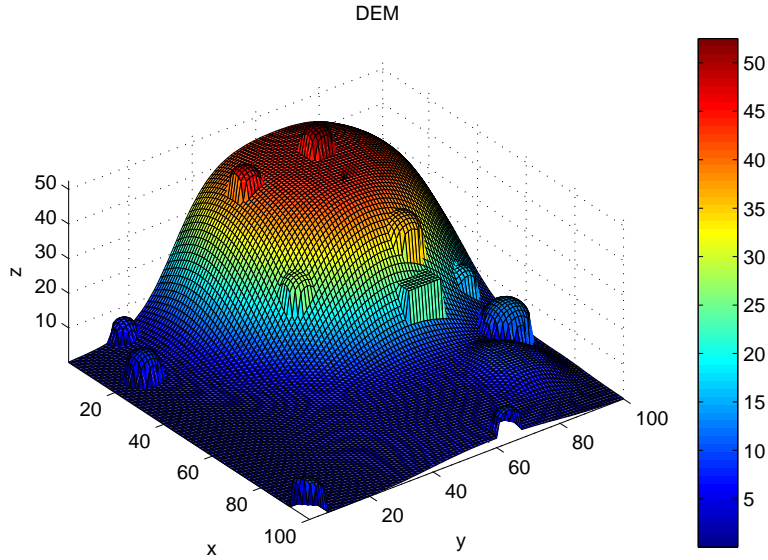


Figure 1.2: The interest map.

At first no gbba is assigned to the uncertain hypothesis  $I \cup NI$ ; subsequently, each expert redistributes part of the basic probability associated to the hypothesis  $I \cap NI$ ,  $NI$ ,  $I$  to the hypothesis  $I \cup NI$ . The gbba are redistributed proportionally to the value  $u$  of the corresponding uncertainty map associated to each expert map, by using the following classical discounting procedure:

$$\left. \begin{aligned} \delta(i) &\leftarrow m(i) \cdot u \\ m(i) &\leftarrow m(i) - \delta(i) \\ m(I \cup NI) &\leftarrow m(I \cup NI) + \delta(i) \end{aligned} \right\} i = I \cap NI, NI, I \quad (1.4)$$

The value of  $u$  depends on the characteristics of the sensor (e.g. measurement errors).

In this work, uncertainty maps will be simulated in order to provide a variety of test cases for the data fusion process. Therefore, the value of  $u$  will not be chosen to reproduce the actual measurements but just to test the proposed methodology. Note that, if the instruments are ideal and no uncertainty in their measurements is present, no mass is assigned to the hypothesis  $I \cup NI$ .

The assignment process presented in Eq. 1.4 is applied to each point on the DEM. Given the three sets of evidence by each expert, the general combination rule for paradoxical sources of DSMT is applied, and the combined evidence is computed. The following step is to compute the belief in the hypothesis *interesting*,  $Bel(I)$ . This value gives a pessimistic estimation (lower boundary) of the probability of that point to be actually interesting. Therefore, the interest map will contain, for each point on the DEM, the belief that point is interesting, according to the high level mission goals. The planner will then give more importance to those areas that are more likely to be interesting, and will reallocate the goals in order to maximise the cumulative value of interest with the highest reliability. In the following section we will present how each maps are generated and how the belief is computed for a specific test case.

#### 1.4 Some Results with DSMT

The proposed approach was initially tested in a simulated environment. A synthetic landscape was generated inserting typical features like rocks with different textures and slopes with different gradients. The algorithm was run simulating the behaviour of the two navigation and the infrared cameras mounted on Nausicaa. The aim of this sample test case was to generate an interest map that was consistent with the simulated features. The result was then used by the planner [5] to generate a set of mission goals in order to visit only the spots that are considered to be the most rewarding in terms of science. The synthetic landscape, represented in Fig. 1.3, was converted into a DEM. The x-y plane in the figure represents an ideal horizontal plane, while z is the elevation of each point of the terrain with respect to this plane. Non-dimensional units for length and temperatures have been used. Assuming that the rover is in the centre of the map, and the height of the camera from the ground is 40 units, it has been possible to calculate whether each point of the map was in sight of the camera or not (Fig. 1.4). As explained above, the module that generates the DEM provides also an uncertainty map based on visibility (partial information about the landscape) and on the intrinsic measurement errors of the digital cameras. The uncertainty map is initially created with values of zero (point in sight, no uncertainty on its elevation) or one (hidden point, no information about its elevation). Then, the uncertainty due to errors of recognition of the disparity maps are simulated by introducing a noise component, with a value in the interval  $[0, 0.2]$ . The resulting uncertainty map is represented in Fig. 1.5.

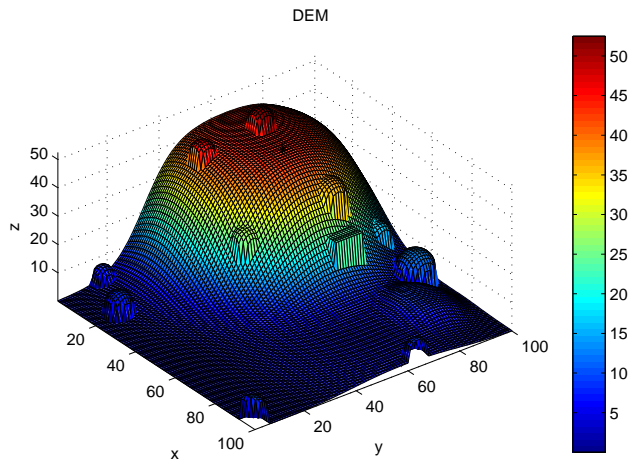


Figure 1.3: DEM of the synthetic landscape: bumped features represent rocks.

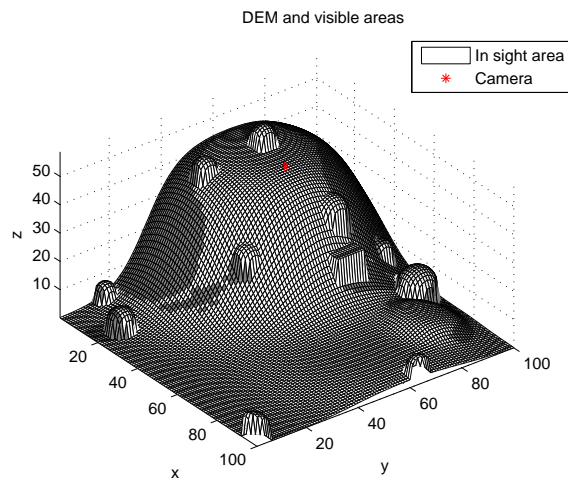


Figure 1.4: Visibility map superimposed on the DEM: in dark grey, surfaces that are not in sight. The camera is in the middle of the map, at a height of 40 units from the ground.

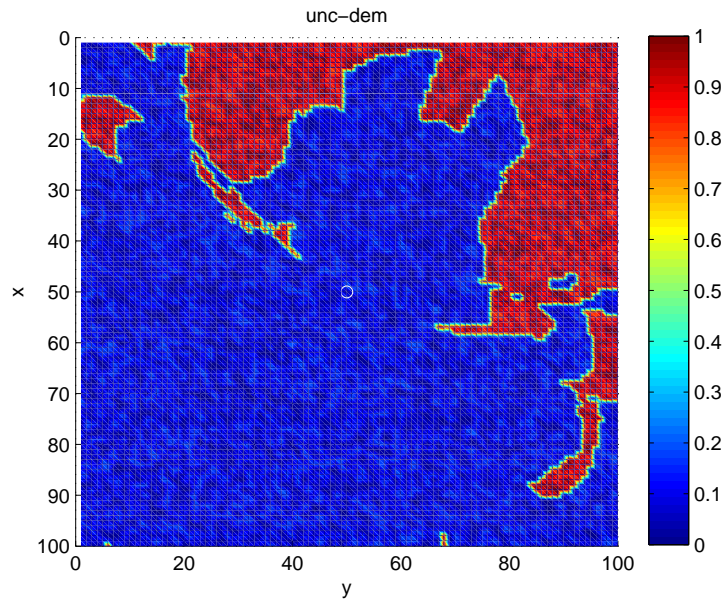


Figure 1.5: The resulting uncertainty map associated to the DEM.

The expert that creates the evidence from the DEM first computes the map of the gradient of the terrain, starting from its elevation; then, it assigns high interest to the points which have a high gradient, and low interest to other points (Table 1.1).

In Fig. 1.6, there is a representation of the absolute value of the gradient of the DEM, as computed by the corresponding expert. The virtual infrared map contains the temperature of the corresponding point on the DEM. The expert associated to the infrared camera assigns high levels of interest to hot areas. The Fig. 1.7 shows the temperature distribution in the virtual environment: the whole terrain as an average temperature below 5 (in the non-dimensional units of temperature) which correspond to a cold terrain, apart from single circular hot area.

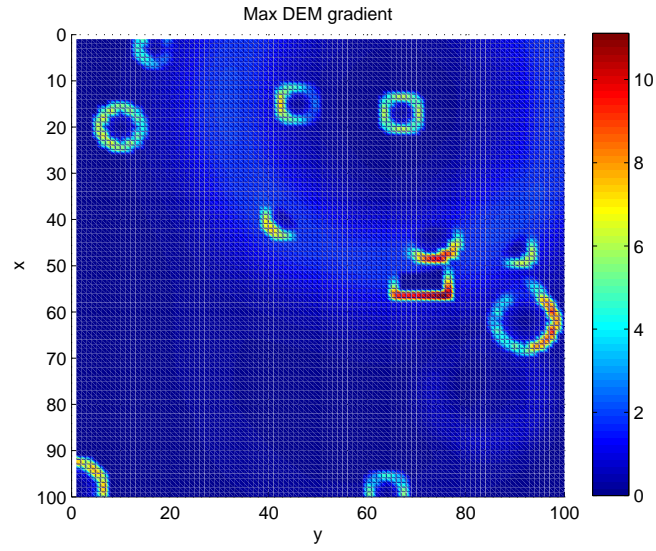


Figure 1.6: Representation of the absolute value of the gradient of the DEM.

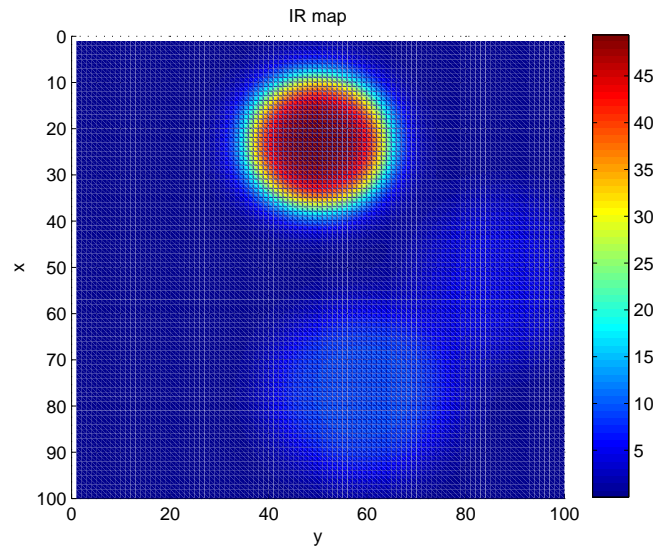


Figure 1.7: The infrared map.



The texture distribution is represented in Fig. ??: four different patterns have been considered, each one corresponding to one colour in the figure. The reference textures with their associated level of interest are stored in a database onboard. The expert of this map assigns the gbba according to the reference values in Table 1.3: it was assumed texture 4 (coloured in brown in Fig. 1.8) has the a greatest probability to be interesting for this particular mission. The experts associated to the texture and infrared maps generate the corresponding uncertainty maps in a similar fashion as the expert of the DEM: they check for visibility of each point and surface in the map. In fact, if the infrared image and optical image are captured simultaneously, without moving the rover, the unknown areas must be the same. However, this yields the same level of uncertainty for the same points on all the three maps. Therefore it was assumed that the uncertainties for the infrared map grows linearly from the bottom end of the map to the upper end of the map, while the uncertainty on the texture grows linearly from the right end to the left end of the map, as shown in Fig. 1.9. Note that this assumption has no particular physical meaning, but it allows us to have areas with very different and mixed levels of uncertainties, thus testing properly the proposed data fusion framework. A different distribution of uncertainty, though producing different values, does not change the significance of the results presented in this chapter. As stated above, in a real case, the uncertainty map would depend on the properties of the instruments and on the level of confidence of the scientists in their own judgement.

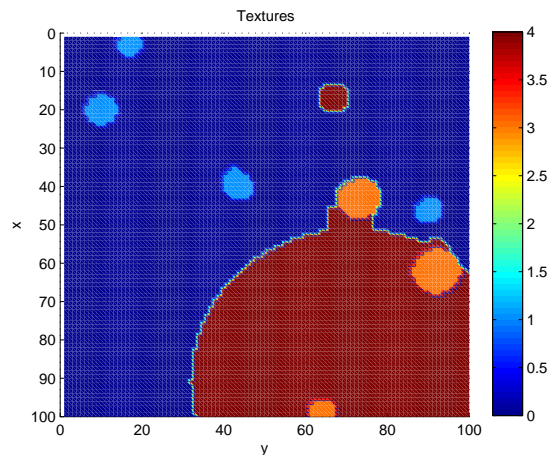


Figure 1.8: The texture map.

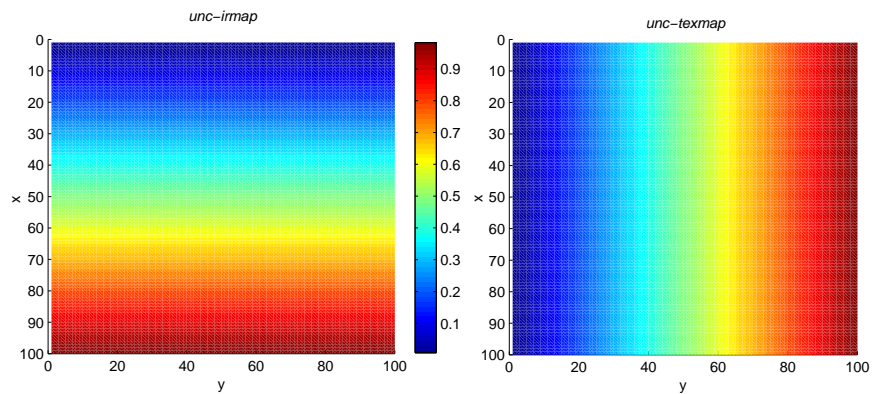


Figure 1.9: The uncertainty associated to the infrared map (left) and to the texture map (right).

Given the maps and the experts, the result of the fusion process, as explained in paragraph 1.3.2, is the interest map shown in Fig. 1.10. The value associated to each point in the map represents the belief that the point is interesting. The areas identified by the letters A, B, C, D, E, F, G, H and I in Fig. 1.10, corresponding to rock borders, are marked as very interesting because of the high gradient value. It shall be noted that only the parts in sight of the cameras are interesting (this is particularly noticeable in the case of spots B, C, D and G). Where the rock is hidden, the gradient is high, but its unreliability is high, as well; thus, the assignment from the expert is uncertain and the associated belief is low. The circular area identified with letter L is considered interesting mainly by the expert of the infrared map but its visibility is high as well as its reliability. In fact, Fig. 1.7 shows that the temperature is high in that area and Fig. 1.9a shows that for that area, the infrared map has a low uncertainty value; thus the information it gives is considered to be very reliable.

The small area with letter M is the most interesting of the whole map, with a value close to one. This is due to the synergy between the DEM and the infrared experts: both have certain information, and the gradient and the temperature are very high. The sudden change in the level of interest on area N is a consequence of the discontinuity of the soil texture, as can be seen in Fig. 1.8. Looking at the map, starting from the area N, and moving right, the degree of interest gradually decreases because the texture information is gradually less reliable on the right part of the map, as can be seen in Fig. 1.9b.

Notice how both the infrared and the DEM expert regarded this area as not interesting but both the DEM and the texture experts stated that the reliability of what observed was good while the infrared stated the opposite. Nonetheless, the fused reliability of the texture and of the DEM maps supports the hypothesis that this area is worth a visit and is safe enough; as a consequence the associated belief is moderately high. Finally a three dimensional representation of the interest map superimposed onto the DEM can be seen in Fig. 1.11.

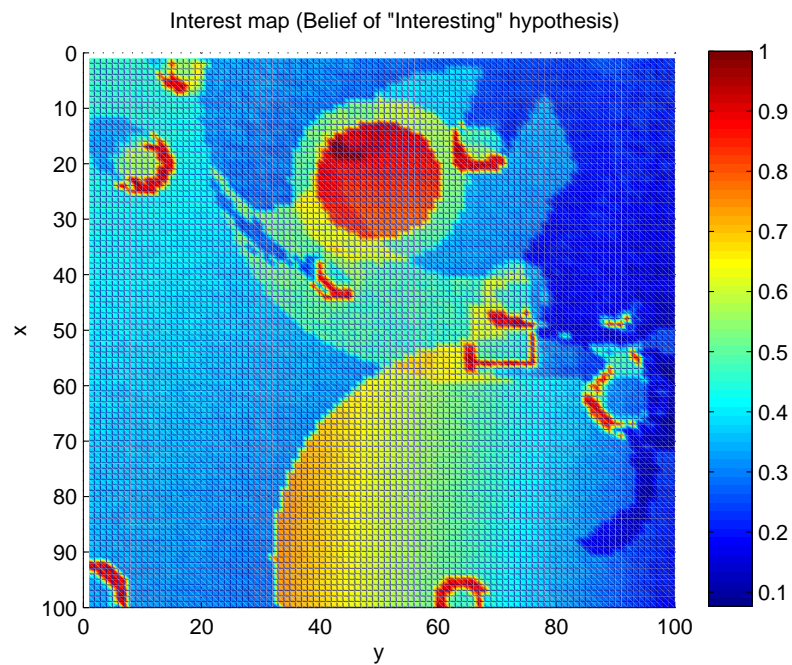


Figure 1.10: Interest map: different colours represent different values of  $Bel(I)$ .

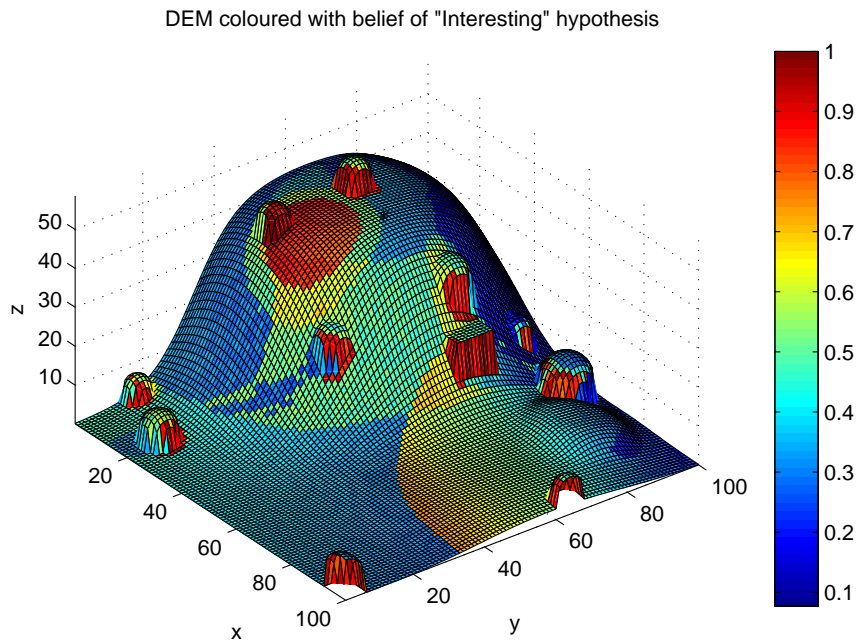


Figure 1.11: Interest map superimposed on the DEM.

#### 1.4.1 DST applied the generation of the Interest Map

The DSMT can be considered as an extension of the Dempster-Shafer Theory of Evidence (DST), from which it was derived. In fact, the DST is a particular case of the DSMT, in which all the sets of a given frame of discernment are disjoint (i.e.,  $\forall A, B \in \Theta, A \neq B \rightarrow A \cap B = \emptyset$ ). As a consequence, the set of possible hypotheses for a frame of discernment  $\Theta = \{\theta_1, \theta_2\}$  is its power set  $2^\Theta = \{\emptyset, A, B, A \cup B\}$ . As for the DSMT, we have  $m(\emptyset) = 0$  and  $\sum_{A \in D^\Theta} m(A) = 1$  but in this case  $D^\Theta$  reduces to  $2^\Theta$ . In literature, the function  $m(\cdot)$  is generally called basic probability assignment (bpa), when referred to the DST framework. There are several different rules for combining bodies of evidence from different experts under this framework. The classical Dempster's rule, which is associative and commutative, fuses the bpa  $m_1$  and  $m_2$  of two experts referred to the same frame of discernment in the following way:

$$m_{12}(A) = \frac{\sum_{\substack{B,C \in 2^\Theta \\ B \cap C = A}} m_1(B)m_2(C)}{1 - \sum_{\substack{B,C \in 2^\Theta \\ B \cap C = \emptyset}} m_1(B)m_2(C)}, \forall A \in 2^\Theta \quad (1.5)$$

The Belief and Plausibility functions are computed in the same way as in the DSmT, that is using Eq. 1.3, given that the power set  $2^\Theta$  shall be considered. The different behaviour of the two theories is evident when conflicting bpa's are given by the experts. In particular, the famous Zadeh's example [10] highlights the counter-intuitive results which the DST can lead to, while the DSmT is able to solve the contradiction in the sources of information quite easily, thank to the presence of the paradoxical hypothesis.

A simple case that brings to quite different results is when the assignments of two different sources are given, as in Table 1.4. In this case, the evidence of the two experts is almost totally conflicting, with a small uncertainty: this situation can happen, for example, when the terrain is flat (then not interesting for the DEM expert) but the texture is very interesting. The fusion through the DST, according to Eq. 1.5, leads to the combined bpa shown in the first column of Table 1.5. The DST combination rule assigns the same amount of evidence to both the hypotheses  $I$  and  $NI$ . In this framework, the value of  $Bel(I)$  is the same as  $m(I)$ . In essence, the DST states that the point has the same probability of being interesting or not interesting, which does not allow the rover to take a decision on whether to investigate that point or not. On the other hand, the DSmT assigns most of the evidence to the paradoxical hypothesis  $I \cap NI$ , which is contributing in the value of  $Bel(I)$ .

	Expert 1	Expert 2
$m_i(I)$	0.99	0
$m_i(NI)$	0	0.99
$m_i(I \cup NI)$	0.01	0.01

Table 1.4: Example of conflicting bodies of evidence for two different experts.

To show the different results in fusing the data using either the DST or the DSmT, let us consider the border of the rock D. As an example, we take the point (67, 20): for this point, we have the values for the gradient of DEM, texture and temperature listed in Table 1.6, with corresponding uncertainties.

According to these values, the consequent bpa (or gbba) are also shown in the same table.

	DST	DSmT
$m_{12}(I)$	0.4975	0.0099
$m_{12}(NI)$	0.4975	0.0099
$m_{12}(I \cup NI)$	0.005	0.0001
$m_{12}(I \cap NI)$	-	0.9801
$Bel(I)$	0.4975	0.99

Table 1.5: Combined evidence and Belief according to DST and DSmT, for evidence provided by the two experts in Table 1.4.

	Value	$m(I \cap NI)$	$m(NI)$	$m(I)$	$m(I \cup NI)$
Gradient of the DEM	6.088	0.15	0.05	0.8	0
Texture	4	0.017	0	0.323	0.66
Temperature	10.23	0.162	0.648	0	0.19

Table 1.6: Values of the three maps at point (67, 20), uncertainties, and corresponding assignments made by the experts.

The result of the combination through the DSmT is shown in Table 1.7. In conclusion, according to the DSmT, the point should be highly interesting, as the belief of the  $I$  hypothesis is close to one.

	DSmT Combined Evidence
$m(I \cap NI)$	0.82293004
$m(NI)$	0.02765400
$m(I)$	0.14941600
$m(I \cup NI)$	0
$Bel(I)$	0.97234607

Table 1.7: Combined evidence and Belief using the DSmT combination rule, for bodies of evidence given in Table 1.6.

The use of the DST, instead, leads to a different result. The DST associative rule can be applied to the same point, but considering that in the DST framework, all the sets are disjoint, so  $I \cap NI = \emptyset$ , it would make no sense to assign bpa to this case. We decided here to reassign the gbba of the hypothesis

$I \cap NI$  to the hypothesis  $I \cup NI$ , as in Table 1.8, since a conflict of opinions would lead to a stall in the decision making process, analogous to a lack of information. Note that, for this case, a different choice of the bpa re-assignment would not change substantially the result obtained with the DST. Applying the DST combination rule, we obtain the evidence in Table 1.9. Then we can state that, using the DST, the belief in the interesting hypothesis is significantly lower than for the DSMT. The border of the rock will not be a primary objective to analyse for the rover in this case.

	$m(NI)$	$m(I)$	$m(I \cup NI)$
Gradient of the DEM	0.05	0.8	$0 + 0.15$
Texture	0	0.323	$0.66 + 0.017$
Temperature	0.648	0	$0.19 + 0.162$

Table 1.8: Re-assignment of the gbpa of the paradoxical hypothesis to the uncertain hypothesis.

Dempster Combined Evidence	
$m(NI)$	0.2296
$m(I)$	0.6881
$m(I \cup NI)$	0.0824
$Bel(I)$	0.6881

Table 1.9: Combined evidence and Belief using the Dempster combination rule, for bodies of evidence given in Table 1.8.

A great number of fusion rules exists, in the DST framework: among those, a set of Proportional Conflict Redistribution rules (PCR) has been studied. The so-called PCR5 is claimed to be the most mathematically exact rule for redistributing the conflicting mass [15]. Since the computation of the combined bpas using the PCR5 becomes quite complicated when more than 2 sources are involved (and in this example they are 3), we decided to show the results of the fusion using the approximated formulation PCR5b. The final masses are obtained in two steps: first, the masses  $m_1(\cdot)$  and  $m_2(\cdot)$  relative to experts 1 and 2 are combined using the DSMT classical rule, obtaining  $m_{12}(\cdot)$ ; then the resulting masses are combined again with source 3, giving  $m_{123}(\cdot)$ . At this point, the conflicting mass  $m_{123}(A \cap B)$  is redistributed proportionally to the basic probability assignments of the experts, according to the rule. If we call  $m_{PCR5b\{12\}3}(\cdot)$  the combined evidence after the redistribution of the conflict, we have:

$$\begin{aligned}
m_{PCR5b\{12\}3}(I) &= m_{123}(I) + m_3(I)m_{12}(I \cap NI) + \\
&\quad m_{12}(I) \frac{m_{12}(I)m_3(NI)}{m_{12}(I) + m_3(NI)} + m_3(I) \frac{m_3(I)m_{12}(NI)}{m_3(I) + m_{12}(NI)} \\
m_{PCR5b\{12\}3}(NI) &= m_{123}(NI) + m_3(NI)m_{12}(I \cap NI) + \\
&\quad m_3(NI) \frac{m_{12}(I)m_3(NI)}{m_{12}(I) + m_3(NI)} + m_{12}(NI) \frac{m_3(I)m_{12}(NI)}{m_3(I) + m_{12}(NI)} \\
m_{PCR5b\{12\}3}(I \cup NI) &= m_{123}(I \cup NI) + m_3(I \cup NI)m_{12}(I \cap NI)
\end{aligned} \tag{1.6}$$

This rule leads to the combined evidence shown in Table 1.10. Although the redistribution of the conflicting masses changed the results slightly with respect to the classical DST combination rule, the difference with the DSMT remains remarkable.

PCR5b Combined Evidence	
$m(NI)$	0.3482
$m(I)$	0.6104
$m(I \cup NI)$	0.0414
$Bel(I)$	0.6104

Table 1.10: Combined evidence and Belief using the PCR5b combination rule, for bodies of evidence given in Table 1.8.

#### 1.4.1.1 Application of DST to a modified frame of discernment

If the frame of discernment is refined in the following way:  $\Theta_{ref} = \{I \cap NI, I/(I \cap NI), NI/(I \cap NI)\}$ , then we can apply DST and obtain a result equivalent to the one computed using DSMT. Given the new refined frame of discernment, the power set is:

$$2^{\Theta_{ref}} = \{\emptyset, X, Y, Z, X \cup Y, X \cup Z, Y \cup Z, X \cup Y \cup Z\} \tag{1.7}$$

where:

$$\begin{aligned}
X &= I \cap NI \\
Y &= I \cup (I \cap NI) \\
Z &= NI \cup (I \cap NI)
\end{aligned} \tag{1.8}$$



Let us denote with prime the bpas referred to the refined frame of discernment. If we assign the bpas for each generic expert  $i$  in the following way:

$$\begin{aligned}
m'_i(X) &= m_i(I \cap NI) \\
m'_i(X \cup Y) &= m_i(I) \\
m'_i(X \cup Z) &= m_i(NI) \\
m'_i(X \cup Y \cup Z) &= m_i(I \cup NI) \\
m'_i(A \in 2^{\Theta_{ref}}, A \neq X, X \cup Y, X \cup Z, X \cup Y \cup Z) &= 0
\end{aligned} \tag{1.9}$$

and the DST combination rule in Eq. 1.5 is applied, we have that:

$$1 - \sum_{\substack{B, C \in 2^{\Theta_{ref}} \\ B \cap C = \emptyset}} m'_1(B)m'_2(C) = 1 \tag{1.10}$$

Computing the bpa, for example, for  $m'_{12}(X)$ , we obtain:

$$\begin{aligned}
m'_{12}(X) &= m'_1(X)m'_2(X) + m'_1(X \cup Y)m'_2(X \cup Z) + \\
& m'_1(X \cup Z)m'_2(X \cup Y) + m'_1(X)m'_2(X \cup Y) + \\
& m'_1(X)m'_2(X \cup Z) + m'_1(X)m'_2(X \cup Y \cup Z) + \\
& m'_2(X \cup Y)m'_2(X) + m'_1(X \cup Z)m'_2(X) + \\
& m'_1(X \cup Y \cup Z)m'_2(X)
\end{aligned} \tag{1.11}$$

On the other hand, applying the DSMT combination rule 1.2 to the standard frame  $\Theta = \{I, NI\}$ , we obtain for  $m_{12}(I \cap NI)$ :

$$\begin{aligned}
m_{12}(I \cap NI) &= m_1(I \cap NI)m_2(I \cap NI) + \\
& m_1(I)m_2(NI) + m_1(NI)m_2(I) + m_1(I \cap NI)m_2(I) + \\
& m_1(I \cap NI)m_2(NI) + m_1(I \cap NI)m_2(I \cup NI) + \\
& m_1(I)m_2(I \cap NI) + m_1(NI)m_2(I \cap NI) + \\
& m_1(I \cup NI)m_2(I \cap NI)
\end{aligned} \tag{1.12}$$

Eq. 1.11 and Eq. 1.12 are equivalent and return the same value. The same happens for  $m'_{12}(X \cup Y \cup Z)$ ,  $m'_{12}(X \cup Z)$ ,  $m'_{12}(X)$ . Therefore, the fusion obtained using the DST with the refined frame of discernment, and the one obtained with the original model and DSMT are identical. Note that, the refinement of the frame of discernment would require a probability assignment to the hypotheses  $I/(I \cap NI)$  and  $NI/(I \cap NI)$  that have little physical meaning and are not intuitive. Therefore, though DST can be used to define the interest map, DSMT offers a more direct definition and treatment of the two

hypotheses  $I$  and  $NI$  without the need for an artificial redefinition of the frame of discernment. Furthermore, it should be noted that DSMT allows the direct treatment of a case in which a source is totally sure about its assignment and therefore cannot assign any probability to the hypothesis  $I \cup NI$ . In this case assigning a probability to the hypothesis  $I \cap NI$  would correspond to allowing some room for discussion and opposite opinions as mentioned above.

## 1.5 Final Remarks

In this chapter, an algorithm for the definition of the level of interest of mission goals for a planetary rover was presented. By fusing navigation data and payload data (infrared camera in this specific case), the rover was endowed with the capability to autonomously assign a level of interest to mission goals. The interest level allows the rover to prioritise, reallocate and choose the most appropriate set of goals depending on contingent situations. The modern theory of Plausible and Paradoxical Reasoning was used to generate an interest map by which the rover can reallocate its goals autonomously in order to maximise the scientific return of the mission. The theory gives the possibility of dealing with vague quantities, like the degree of interest of an object. In particular, the advantage of DSMT is the possibility to directly assign a level of interest to hypothesis  $I$  and  $NI$  for each point of the DEM, leaving room for potential disagreements among the scientists or between the scientists and the ground control team. The results showed that the proposed approach is suitable to uniquely identify the interesting zones, given the high level scientific goals of the mission. The goals can be easily modified or tuned, by changing the experts used into the data fusion process.

## 1.6 Acknowledgments

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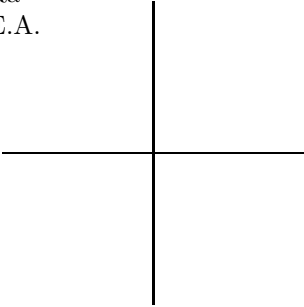
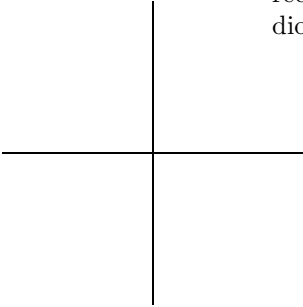


## Biographies of contributors

*Matteo Ceriotti* was born near Milan, Italy, on June 15, 1980. He received the M.Sc. summa cum laude from Politecnico di Milano in 2006 with a thesis on “Non Deterministic Planning and Data Fusion with the Evidence Theory”. The thesis was part of a study for planetary rover autonomy in collaboration with the European Space Agency. At present, he is a Ph.D. candidate at the Department of Aerospace Engineering of the University of Glasgow, United Kingdom. His study is focused on global optimisation for multi-gravity assist interplanetary trajectories. His research interests are space mission analysis, global optimisation, spacecraft autonomy and artificial intelligence.  
Address: Department of Aerospace Engineering, University of Glasgow, James Watt South Building, G12 8QQ, Glasgow, UK.  
E-mail: [m.ceriotti@eng.gla.ac.uk](mailto:m.ceriotti@eng.gla.ac.uk)

*Milan Daniel* was born in Prague in 1962. He graduated in the Faculty of Mathematics and Physics of Charles University Prague in 1985. He defended his PhD thesis in the Institute of Computer Science of the Academy of Sciences of the Czech Republic in 1993. His research activities have been always related to the Institute, the department of Theoretical Computer Science, formerly the department of Knowledge Based Systems. Author’s current main scientific interests are belief functions, namely combination of belief functions and probabilistic transformations of belief functions. The other interests are uncertainty processing, fuzzy logic and knowledge based systems.  
Address: Institute of Computer Science, Academy of Sciences of the Czech Republic, Pod vodárenskou věží 2, CZ - 182 07 Prague 8, Czech Republic.  
Web page: <http://www.cs.cas.cz>  
E-mail: [milan.daniel@cs.cas.cz](mailto:milan.daniel@cs.cas.cz)

*Jean Dezert* was born in l’Hay les Roses, France, on August 25, 1962. He received the electrical engineering degree from the Ecole Française de Radioélectricité Electronique and Informatique (EFREI), Paris, in 1985, the D.E.A.



degree in 1986 from the University Paris VII (Jussieu), and his Ph.D. from the University Paris XI, Orsay, in 1990, all in Automatic Control and Signal Processing. During 1986-1990 he was with the Systems Department at the Office National d'Études et de Recherches Aérospatiales (ONERA), Châtillon, France, and did research in tracking. During 1991-1992, he visited the Department of Electrical and Systems Engineering, University of Connecticut, Storrs, U.S.A. as an European Space Agency (ESA) Postdoctoral Research Fellow. During 1992-1993 he was teaching assistant in Electrical Engineering at the University of Orléans, France. Since 1993, he is senior research scientist in the Image Estimation and Decision (IED) Research Lab. with the Information and Modelling and Processing Department (DTIM) at ONERA. His current research interests include autonomous navigation, estimation theory, stochastic systems theory and its applications to multisensor-multitarget tracking (MS-MTT), information fusion, plausible reasoning and non-standard Logics. Dr. Jean Dezert is developing since 2001 with Professor Smarandache a new theory of plausible and paradoxical reasoning for information fusion (DSmT) and has edited the first textbook (collected works) devoted to this new emerging research field published by American Research Press, Rehoboth in 2004. He owns one international patent in the autonomous navigation field and has published several papers in international conferences and journals. He coauthored a chapter in *Multitarget-Multisensor Tracking: Applications and Advances*, Vol.2, 1990 (Y. Bar-Shalom Editor). He is member of IEEE and of Eta Kappa Nu, serves as reviewer for different International Journals, teaches a MS-MTT and Data Fusion course at the French ENSTA Engineering School, collaborates for the development of the International Society of Information Fusion (ISIF) since 1998, and has served as Local Arrangements Organizer for the Third International Conference on Information Fusion, FUSION 2000, July 10-13, in Paris. He has been involved in the Technical Program Committees of Fusion 2001-2004 International Conferences. Since 2001, he is a member of the board of the International Society of Information Fusion (<http://www.isif.org>) and served as Secretary for ISIF in 2001-2003. He served also as executive vice-president of ISIF in 2004. In 2003, he organized with Professor Smarandache, the first special session devoted to plausible and paradoxical reasoning for information fusion at the International conference on Information Fusion, Fusion 2003, Cairns, Australia and also a panel discussion and a special session on DSmT at Fusion 2004, Stockholm in June 2004. Dr. Dezert gave several invited seminars and lectures on Data Fusion and Tracking during recent past years. He also participates as member to Conference Technical Committee of Fusion 2005, Fusion 2006 International Conference on Information Fusion and Fuzzy Sets and Technology Conference, Salt Lake City, USA in July 2005. He is also Associate Editor of *Journal of Advances in Information Fusion (JAIF)*.

Address: Office National d'Études et de Recherches Aérospatiales (ONERA),  
Département Traitement de l'Information et Modélisation, BP-72, 29 Avenue  
de la Division Leclerc, 92322 Châtillon Cedex, France.

Web page: <http://www.gallup.unm.edu/~smarandache/DSmT.htm>

E-mail: [jean.dezert@onera.fr](mailto:jean.dezert@onera.fr), [jdezert@gmail.com](mailto:jdezert@gmail.com)

*Catholijn M. Jonker* obtained her MSc in Computer Science from the University Utrecht in 1990 after which she obtained her PhD in Artificial Intelligence from the same university in 1994. After positions at various universities, she currently is full professor Man-Machine Interaction with the faculty of Electrical Engineering, Mathematics and Computer Science at the Delft University of Technology. In 2005 and 2006 Prof. Catholijn Jonker was chair of the Young Academy (De Jonge Acedemie) of the Royal Netherlands Academy for Sciences (KNAW) in the Netherlands. In 2008 Catholijn Jonker was granted a prestigious national VICI innovation grant for her project called The Pocket Negotiator.

Address: Delft University of Technology, Faculty of Electrical Engineering, Mathematics and Computer Science, Man-Machine Interaction Group, 2628 CD Delft, the Netherlands.

Web page: [www.mmi.tudelft.nl](http://www.mmi.tudelft.nl)

E-mail: [c.m.jonker@tudelft.nl](mailto:c.m.jonker@tudelft.nl)

*Adam Kawalec* was born in Poland in 1949. He received his M.Sc. degree in solid state electronics and his Ph.D degree from the Department of Technical Physics, and his D.Sc. degree in electronics, acoustoelectronics from the Department of Electronics, Military University of Technology, Warsaw, Poland in 1974, 1980, 2002, respectively. In 1974, he joined the Military University of Technology, Department of Technical Physics, Warsaw, Poland, where he was involved in surface acoustics waves convolvers research. Since 1979, he has tested SAW dispersive delay lines applied in radar pulse compression systems and SAW sensors. He is currently an Associate Professor of the Department of Electronics, Military University of Technology, Warsaw, Poland, where he teaches courses in acoustoelectronics and the basic of telecommunications. Professor Kawalec is a Head of the Institute of Radioelectronics, Department of Electronics, Military University of Technology, Warsaw, Poland. He is the author and co-author of more than 120 scientific papers published in international and national journals and conference proceedings and co-inventor of five patents.

Address: The Institute of Radioelectronics, WAT Military University of Technology, Warsaw, Poland.



E-mail: [Adam.Kawalec@wat.edu.pl](mailto:Adam.Kawalec@wat.edu.pl)

*Ksawery Krenc* was born in Poland in 1975. He received his M.Sc. in Automatics and Robotics, Faculty of Electronics Telecommunication and Informatics from The Technical University of Gdansk in 2001. In 2002, he joined RD Marine Technology Centre, as a program writer. In 2004, he got promoted to the analyst position. He elaborated the specification of data collecting and data fusion applications for Leba-3 (Polish Marine C&C system). Since 2006, he has been publishing solutions related to data (and information) fusion for C&C systems' purposes. In 2007, he got promoted to the senior analyst position. Since 2007 up to now, he has been the Sensor Networks research team manager in Polish NEC consortium. He is currently working towards Ph.D. degree. His current research interests focus on information fusion for the purpose of C&C systems with a particular emphasis on applying evidential theories like Dempster-Shafer Theory and Dezert-Smarandache Theory.

Address: RS-SD, R&D Marine Technology Centre, Gdynia, Poland.

E-mail: [ksawery.krenc@ctm.gdynia.pl](mailto:ksawery.krenc@ctm.gdynia.pl)

*Xinde Li* was born in Shandong province, China, on September 30, 1975. He graduated from Shenyang institute of chemistry technology, Shenyang, China in 1997 and he received his Master degree from Shandong University, Jinan, China in 2003 and his Ph. D. degree from Huazhong University of Science and Technology, Wuhan, China, in 2007. Currently, he works as a Lecturer in the School of Automation, Southeast University, China. His main research interests include information fusion, robot perception, computer vision, pattern recognition, robot's map building and localization and multi-robot system.

Address: Institute of Intelligent Robot and Intelligent Control, School of Automation, Southeast University, Si Pai Lou 2#, Nanjing 210096, China.

E-mail: [xindelili@seu.edu.cn](mailto:xindelili@seu.edu.cn)

*Arnaud Martin* was born in Bastia, France in 1974. He received the Ph.D. degree in Signal Processing (2001), and the Master degree in Probability (1998) from the university of Rennes, France. Dr. Arnaud Martin worked on speech recognition during three years (1998-2001) at France Telecom R&D, Lannion, France. He worked in the department of statistic and data mining (STID) of the IUT of Vannes, France, as temporary assistant Professor (ATER) during two years (2001-2003). In 2003, he joined the laboratory E<sup>3</sup>I<sup>2</sup>: EA3876 at the ENSIETA, Brest, France, as a teacher and researcher. Dr. Arnaud Martin teaches mathematics, data fusion, data mining, signal processing and computer sciences. His research interests are mainly related to the belief functions for

the classification of real data and include data fusion, data mining, signal processing especially for sonar and radar data.

Address: ENSIETA E<sup>3</sup>I<sup>2</sup> Laboratory, 2, rue François Verny, 29806 Brest Cedex 9, France.

Web page: <http://www.ensieta.fr/e3i2/Martin>

E-mail: [Arnaud.Martin@ensieta.fr](mailto:Arnaud.Martin@ensieta.fr)

*Florentin Smarandache* was born in Balcesti, Romania, in 1954. He got a M. Sc. Degree in both Mathematics and Computer Science from the University of Craiova in 1979, received a Ph. D. in Mathematics from the State University of Kishinev in 1997, and continued postdoctoral studies at various American Universities (New Mexico State Univ. in Las Cruces, Los Alamos National Lab.) after emigration. In 1988 he escaped from his country, pasted two years in a political refugee camp in Turkey, and in 1990 emigrated to USA. In 1996 he became an American citizen. Dr. Smarandache worked as a professor of mathematics for many years in Romania, Morocco, and United States, and between 1990-1995 as a software engineer for Honeywell, Inc., in Phoenix, Arizona. In present, he teaches mathematics at the University of New Mexico, Gallup Campus, USA. Very prolific, he is the author, co-author, and editor of 75 books, over 100 scientific notes and articles, and contributed to about 50 scientific and 100 literary journals from around the world (in mathematics, informatics, physics, philosophy, rebus, literature, and arts). He wrote in Romanian, French, and English. Some of his work was translated into Spanish, German, Portuguese, Italian, Dutch, Arabic, Esperanto, Swedish, Farsi, Chinese. He was so attracted by contradictions that, in 1980s, he set up the "Paradoxism" avant-garde movement in literature, philosophy, art, even science, which made many advocates in the world, and it's based on excessive use of antitheses, antinomies, paradoxes in creation - making an interesting connection between mathematics, engineering, philosophy, and literature and led him to coining the neutrosophic logic, a logic generalizing the intuitionistic fuzzy logic that is able to deal with paradoxes. In mathematics there are several entries named Smarandache Functions, Sequences, Constants, and especially Paradoxes in international journals and encyclopedias. He organized the "First International Conference on Neutrosophics" at the University of New Mexico, Dec. 1-3, 2001. Small contributions he had in physics and psychology too. Much of his work is held in "The Florentin Smarandache Papers" Special Collections at the Arizona State Univ., Tempe, and Texas State Univ., Austin (USA), also in the National Archives (Rm. Vâlcea) and Romanian Literary Museum (Bucharest), and in the Musée de Bergerac (France). In 2003, he organized with Jean Dezert, the first special session devoted to plausible and paradoxical reasoning for information fusion at the Fusion 2003 Int. conf. on

Information Fusion in Cairns, Australia.

Address: Dept. of Math., Univ. of New Mexico, 200 College Road, Gallup, NM 87301, U.S.A.

Web page: <http://www.gallup.unm.edu/~smarandache/>

E-mail: [smarand@unm.edu](mailto:smarand@unm.edu).

*Albena Tchamova* is Associate Professor at the Department of Mathematical Methods for Sensor Information Processing, Institute for Parallel Processing, Bulgarian Academy of Sciences. She received M.Sc. degree in Microelectronics and Ph.D. degree in Radiolocation and Radionavigation (Target Attributes Identification and Classification on the base of Evidence Reasoning Theory and Fuzzy Logic) from the Technical University of Sofia, Bulgaria, in 1978 and 1998 respectively. She worked as a researcher in numerous academic and industry projects (Bulgarian and international) in the area of Multisensor Multitarget Tracking (MS-MTT) and Data Fusion. She is a member of the IEEE, member of International Society for Information Fusion (ISIF), Association of European Operational Research Societies on Fuzzy Sets (EUROFUSE), Image Recognition Society, BAS. Dr. Tchamova's current research interests include MS-MTT, Target Identification, Dezert-Smarandache Theory of Plausible and Paradoxical Reasoning, Information Fusion, Decision Making under Uncertainty.

Address: Institute for Parallel Processing, Bulgarian Academy of Sciences, "Acad. G. Bonchev" Str., bl.25-A, 1113 Sofia, Bulgaria.

E-mail: [tchamova@bas.bg](mailto:tchamova@bas.bg).

*Willem L. van Norden* obtained his MSc Media and Knowledge Engineering in 2005 with the Delft University of Technology. During his active career in the Royal Netherlands Navy he was commissioned on an Air Defense and Command frigate as a System Responsible Officer and Lt. Wilbert van Norden is now commissioned as Business Analyst at Force Vision, the centre for automation of mission-critical system of the Defense Material Organization in the Netherlands. He works in the Planning and Decision Support department, where he focusses on sensor management concepts and automated classification support. For his MSc thesis titled *Intelligent task scheduling in sensor networks: Introducing three new scheduling methodologies* Wilbert van Norden received the best thesis award 2005 from the The Hague chapter of the Armed Forces Communications and Electronics Association (AFCEA).

Address: CAMS – Force Vision, MPC 10A, P.O. Box 10000, 1780 CA, Den Helder, the Netherlands.

Web page: [www.forcevision.nl](http://www.forcevision.nl)

E-mail: [w.l.van.norden@forcevision.nl](mailto:w.l.van.norden@forcevision.nl)

*Massimiliano Vasile* received his Master and Ph.D. degrees from the Department of Aerospace Engineering of Politecnico di Milano, Italy, in 1996 and 2000 respectively. From 2001 to 2003 he worked as Research Fellow in the Advanced Concepts Team of the European Space Agency (ESA), on new methods for Space Mission Analysis and Design and Trajectory Optimization. From 2004 to 2005 he worked as a lecturer in Space System Engineering in the Department of Aerospace Engineering of Politecnico di Milano. Since 2005, he has been a Lecturer in the Department of Aerospace Engineering and Head of Research for the Space Advanced Research Team at the University of Glasgow (<http://www.aero.gla.ac.uk/Research/SpaceArt>). His main research interests are: Space Mission Analysis and Design, Global and Multiobjective Optimization, Bio-inspired Optimization Methods, Asteroids, Evolutionary Computation, Concurrent Engineering, Multidisciplinary Design, Swarm Intelligence, Formation Flying, Autonomous Robotic Systems. He is member of the IEEE, AIAA and AIRO.

Address: Department of Aerospace Engineering, University of Glasgow, James Watt South Building, G12 8QQ, Glasgow, UK.

E-mail: [m.vasile@aero.gla.ac.uk](mailto:m.vasile@aero.gla.ac.uk)

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