Global Safety Map (LIDAR and NFT) Algorithm Description Document

Overview

This data product supports the Safety Map requirement SM.G.4.23: "*SPOC shall develop the software to produce the global Lidar-based safety score map by convolving the safety score with deliverability at the GSM resolution according to the SPOC-SSM ICD (UA-ICD-9.4.4-1014).*" and SM.G.4.32: *"SPOC shall develop the software to produce a global NFT-based safety map by assigning the safety score values on the GSM according to the SPOC-SSM ICD (UA-ICD-9.4.4-1014)."* Here we provide the algorithm description for the generation of the per-facet probability assessment of global safety. The safety map probability algorithm will provide an approach for selecting and ranking the candidate sample sites.

Inputs

- Global DTM (0.75m nominal resolution)
- Global Tilt Input Map
- Global Roughness Input Map
- Global Thermal input Map
- Global Reflectivity Map (LIDAR-Based Map only)
- Global Plume Map
- Global Gravity Uncertainty Input Map (NFT-based Map only)

Outputs

- Global Safety Probability Map (probabilistic assessment, one each for LIDAR and NFT-based)
  - Per-facet calculation

Algorithms

Two algorithms for the Global Safety Map will be created, one that uses LIDAR guidance and one that uses NFT guidance. The implementation of both algorithms is based on a Bayesian network where the conditional interdependence between the different user variable parameters are captured in a network and Bayesian theory is systematically applied to compute the final safety probability. Note that the same Bayesian network algorithm can be set up to model conditional independence between each of the inputs, based on the selected algorithm parameters.

Conditional Independence-based Algorithm

This algorithm computes the per-facet probability of safety of the spacecraft according to the following formula, assuming LIDAR guidance.

$$p(Safety = True) = p(Tilt = Safe)p(Roughness = Safe)p(Thermal = Safe)p(Reflectivity = Safe)p(Plume = Present)$$

This algorithm computes the per-facet probability of safety of the spacecraft according to the following formula, assuming NFT guidance.

$$p(Safety = True) = p(Tilt = Safe)p(Roughness = Safe)p(Thermal = Safe)p(Gravity\ Uncertainty = Safe)p(Plume = Present)$$

The algorithm assumes that there is no conditional dependency between input variables as well as with the safety of the spacecraft (no conditional dependency between the state of the spacecraft safety and the state of the input parameters). The probabilities of the input parameters are computed using the procedure identical to the one described in section “Input variable selection and nature of the node”.

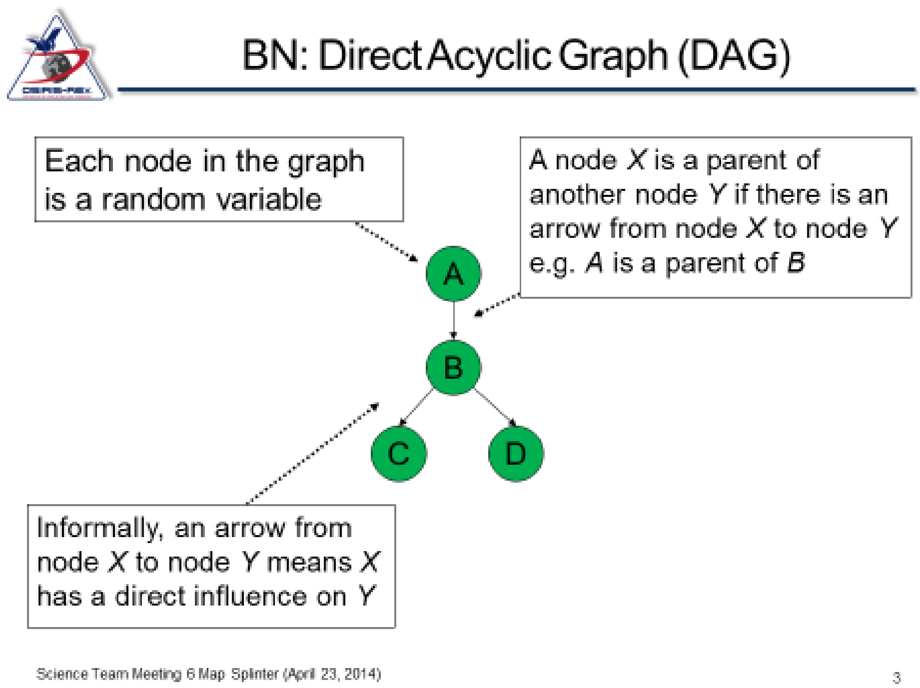

Figure 1. Bayesian Network is represented as a Direct Acyclic Graph

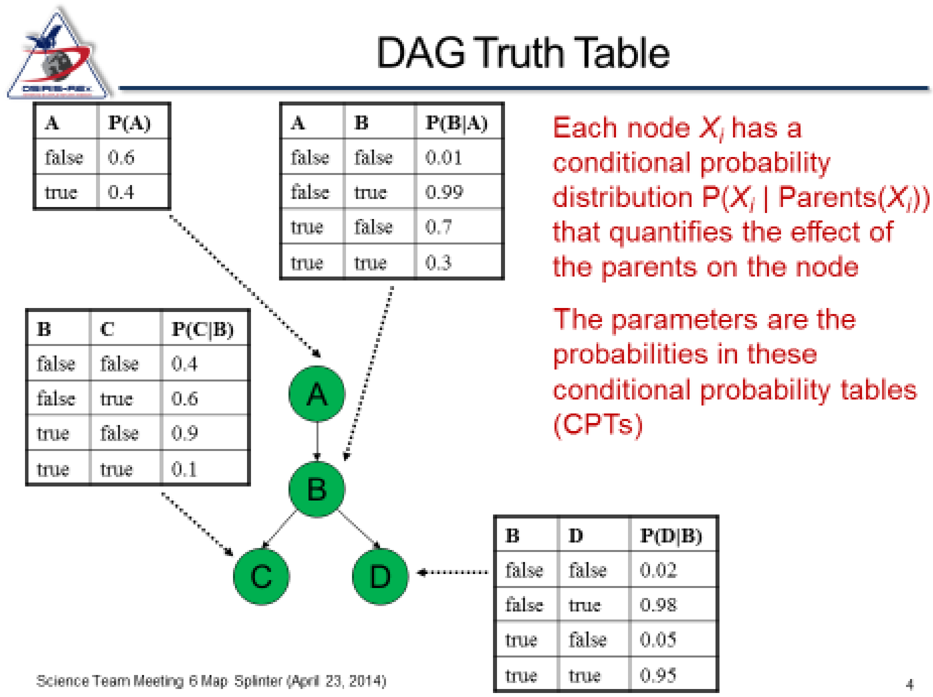

Figure 2. Conditional Probability Tables.

Bayesian Network Algorithm

A Bayesian Network (BN) is a graphical model that efficiently encodes the joint probability distribution for a defined set of variables. A BN for a set of variables X= {X_1,….X_n} contains 1) Network structure S encoding the conditional independence assertions about X and 2)a set P of local probability distributions. The network structure S is a Directed Acyclic Graph (DAG) where the Nodes are the one-to-one correspondence with the variables X (Figure 1.). Note that presence of an arc implies conditional dependence whereas lack of an arc denotes conditional independence. Generally, the joint probability distribution can be factorized as product of conditional probability as captured by the DAG structure:

$$P(X_1 = x_1, \ldots, X_n = x_n) = \prod_{i=1}^{n} P(X_i = x_i \mid Parents(X_i))$$

Conditional probability is encoded in the Conditional Probability Table (CPT). Each node has a conditional probability distribution that quantifies the effect of the parents on the node. The CPTs capture such probabilities (Figure 2.)

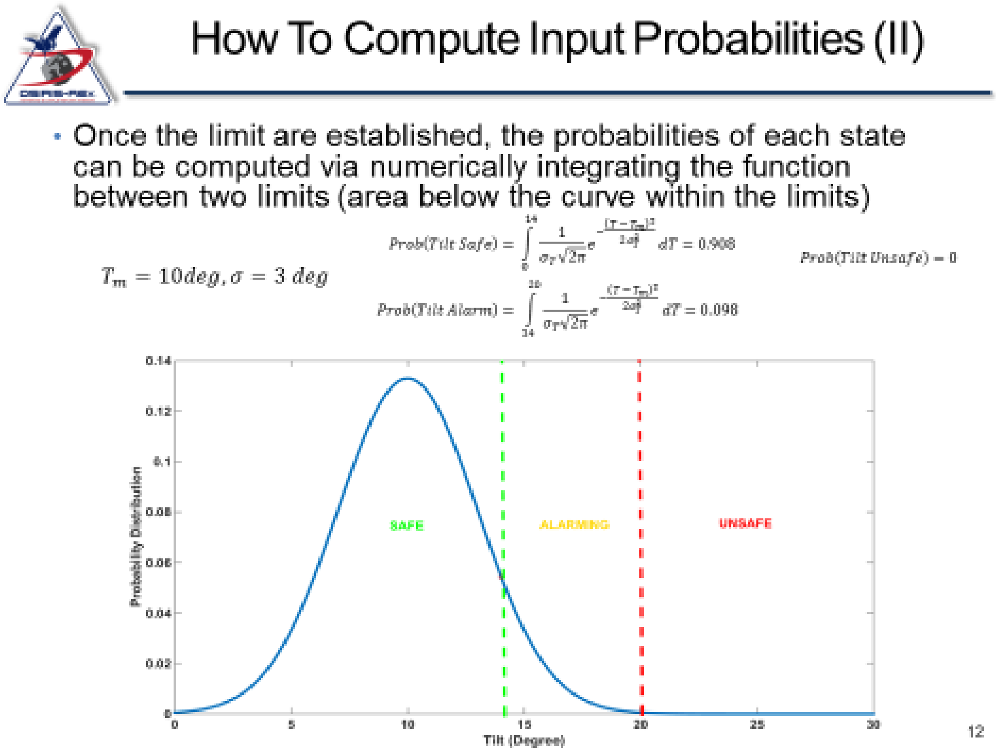

Figure 3. Example of how to transform the Tilt input and its uncertainty into probabilistic inputs to the BN

Bayesian Network for Global Safety Assessment

The steps necessary for constructing a Bayesian network to compute the per-facet global safety probability are:

1. Select the input variables and define the nature of the node
2. Define the DAG structure
3. Define the Conditional Probability Tables (CPTs)

Input variable selection and nature of the node

The input variables are defined by the problem and are established to be Tilt, Roughness, Thermal, Reflectivity or Gravity Uncertainty (depending on the guidance method) and Plumes. Each variable represent an input node in the network and is assumed to be “discrete”, i.e. can take three states, i.e. “safe”, “alarming“ and “unsafe”. Each input value per facet (e.g. tilt and its uncertainty) is processed to evaluate the likelihood of being safe, alarming and unsafe for spacecraft safety. The approach is the following: We model the probability distribution of the data as a Gaussian (normal distribution) with parameter as mean and use standard deviation as uncertainty on the value. For example, for a the tilt input given the value T_{ms} and the standard deviation σ_T, we model the pdf as follow:

$$pdf(T) = \frac{1}{\sigma_T\sqrt{2\pi}} e^{-\frac{(T-T_m)^2}{2\sigma_T^2}}$$

Once the limits of safe/alarming/unsafe are established the integral over the limits determine its probability input. Figure 3. Shows an example for the case of Tilt input with value of 10 degrees and uncertainty of 3 degrees (1-sigma).

DAG Definition and CPT structure

The current DAG representing the BN for global safety probability calculation is reported in Figure 4. Sample of CPTs (both deterministic and probabilistic) are reported in Figure 5. Structure of the DAG and the CPTs are subjected to future updates pending improvement of our understanding of the relationship between nodes and the conditional dependencies within the variables of the problem space.

Implementation

The BN is implemented in a commercial software called NETICA (NORSYS Software Corp., version 5.1.5) which is a framework for rapid prototyping of bayesian networks. The input maps (per facet) are processed using MATLAB script and interfaces with NETICA using the NETICA Java API (version 5.04)

Candidate Site Selection and Ranking

The per-facet safety probability calculations will be considered as “Safety Score” and employed to select and rank the candidate sample sites.

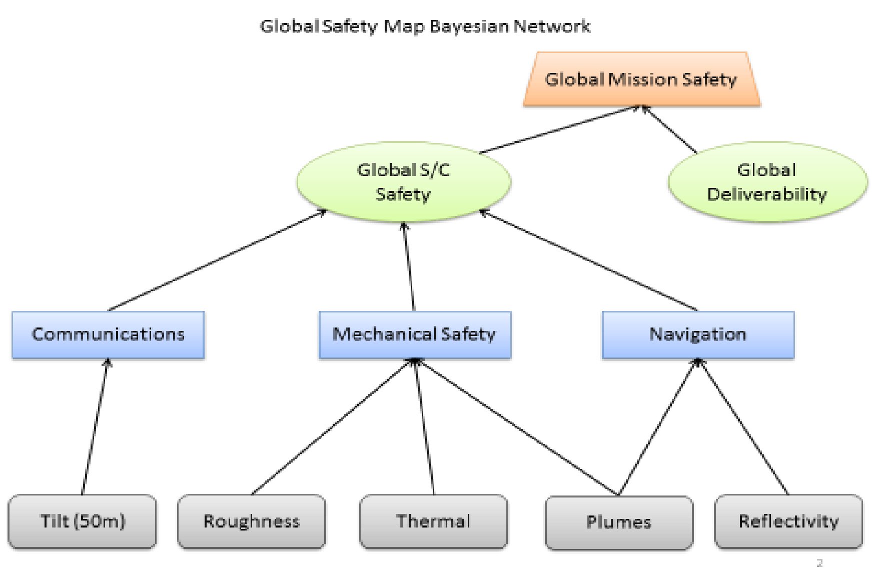

Figure 4. Current Version of the DAG for the Global Safety Map

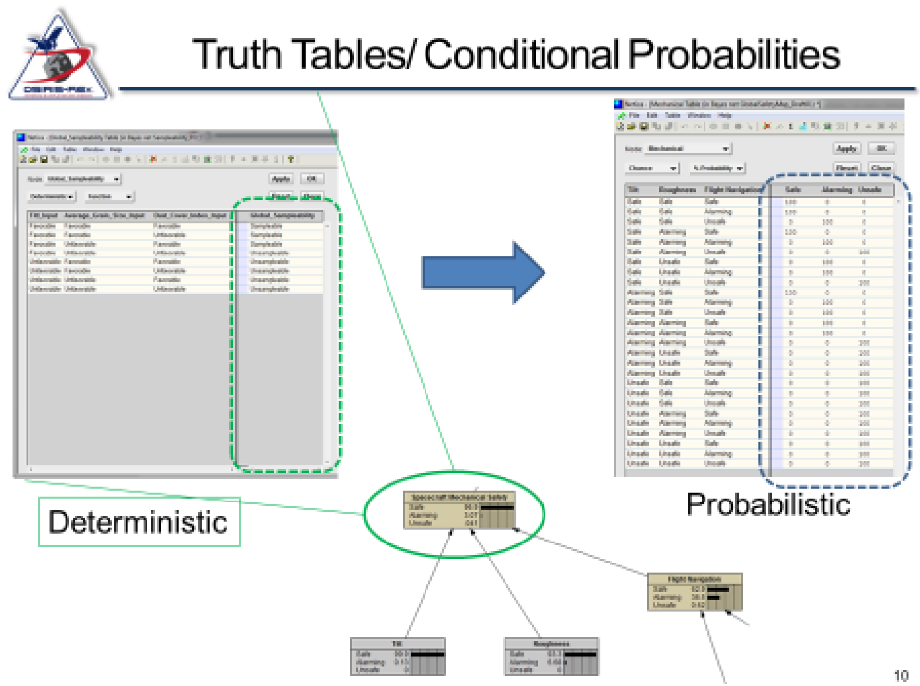

Figure 5. Example of Conditional Probability tables (both deterministic and probabilistic) as implemented in NETICA.