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SIMULATING AIR TRAFFIC BLOCKAGE DUE TO CONVECTIVE WEATHER CONDITIONS

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ABSTRACT

A Monte Carlo methodology is proposed for simulating air traffic blockage patterns under the impact of convective weather. The simulation utilizes probabilistic convective weather forecasts such as those produced by the 1-6 hour National Convective Weather Forecast. A matrix of random numbers is fed to the simulation process to obtain an instantiation of traffic blockage maps. Gaussian smoothing with varying Full Width at Half Maximum across the grid is employed to model the varying spatial correlation between cells. Special Cellular Automata techniques are employed to model the evolvement, i.e. the trend, growth, and dissipation of convection, between consecutive time intervals. Model parameters are obtained from analyzing historical convective weather data. A software tool is also developed to implement the simulation methodology. The simulation methodology thus provides a means to improve the utilization of short term probabilistic convective weather forecast products, and to improve air traffic efficiency in the large.

1 INTRODUCTION

An important problem in air Traffic Flow Management (TFM) is the determination of airspace capacity as a function of weather conditions. However, characterization of the relationship between different weather patterns and capacity is a difficult task due to the uncertainty in weather conditions. The complexity of weather patterns and transitions makes it impossible to use analytical studies for this purpose. Hence, simulation exists as the most amenable tool for the problem.

In this study, we develop an easy-to-implement weather model that may be used with in the context of simulation to study the evolution of a given weather event over multiple time intervals in an airspace of rectangular shape. In our model, a generic airspace is partitioned into a two dimensional grid, and the time is divided into equal time intervals. The dimensions of each cell in the grid are determined by the resolution required by the TFM algorithms, i.e. conflict detection and traffic re-routing. This resolution may not necessarily be the same as that in the probabilistic weather forecast data. Although the model is described using a two-dimensional (2D) grid structure, the approach can be extended to three-dimensions.

Several models exist for simulating weather (Johnson et al. 1996; McQueen et al. 1997). Most advanced weather simulation models require as inputs a large amount of data describing the existing conditions at a given location. This data is processed and probabilistic movement patterns are developed according to the values of certain parameters, such as temperature, pressure, wind speed and direction. However, rather than being an advanced and detailed weather simulation model, the model proposed in this study is a generic simulation tool that is used in studying the effects of convective weather on airspace capacity.

Airspace capacity is defined as the number of aircraft that can fly through the airspace during a fixed time inter-

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val. This capacity is dependent on the weather conditions and traffic flow patterns within the airspace, and is stochastic due to the uncertainty in weather and traffic flow patterns. Our weather simulation model is part of a larger model, which is used to determine probability distributions of airspace capacity by conducting Monte Carlo simulations of the traffic flow within the generic sector over the range of possible scenarios, where a scenario is a unique combination of an instantiation of the weather pattern, and an instantiation of the traffic pattern. Specifically, the weather model described in this study is used in generating scenarios of weather movements. The only inputs to the model are the probabilistic weather forecasts for the blockage status of a given area and an initial weather event, in which blockage means that the area is not available for air traffic.

The remainder of this paper is organized as follows. In Section 2, we describe the input required for the simulation model. An overview of the modeling approach is presented in Section 3, while the smoothing and cellular automata methodologies used in the model are described in Sections 4 and 5, respectively. The software implementation for the simulation model is described in Section 6, and followed by the conclusions in Section 7.

2 MODEL INPUT: PROBABILISTIC WEATHER FORECASTS

The developed simulation model assumes the availability of probabilistic weather forecasts, such as the 1-6 hour National Convective Weather Forecast (NCWF-6, see Pinto 2006 and Pinto et al. 2006). The probabilistic forecasts of convection are based on blending radar-based extrapolation forecasts and Rapid Update Cycle (RUC)-based Convective Probability Forecasts (RCPF) of convection (Weygandt and Benjamin 2004). The RCPF is a derived product that uses output (e.g. forecasted rainfall rates) from the latest operational version of the RUC model (Benjamin et al. 2004) while the radar-based probabilities are produced using a combination of extrapolation and trending, and includes growth and dissipation of convection (Megenhardt et al. 2004).

The forecast probabilities indicate the likelihood that aviation disrupting convection will be present at a given location at the given forecast time (Pinto 2006). The data are provided at nodes on a Lambert Conformal projection grid with a 4-km resolution at latitude 25º north. The grid covers the contiguous United States (CONUS). Generally speaking, a Video Integration Processor (VIP) level of 3.5 is typically used as a minimum threshold above which convection is expected to impact aviation both en route and departures and landings. VIP is a measurement derived from the WSR-88D Level 3 data product. A VIP level of 3 corresponds to a radar reflectivity of 40 dBZ and a Vertically Integrated Liquid (VIL) of between 3.5 and 6.9 kg/m^2 (Pinto 2006; Hallowell et al. 1999). The threshold used by NCWF-6 is thus a radar reflection of 40 dBZ.

The probability maps can also be used to derive the forecasted coverage of storms (Pinto 2006). For example, a user may be interested in areas with coverage probabilities exceeding 40%. This can be determined by contouring the region accordingly. In a perfectly reliable forecast, one would expect 40% of the area within this contour to have aviation-impacting convection. The system is currently being evaluated by a select group of users and scientists. Development of the system is funded by the Federal Aviation Administration (FAA) Aviation Weather Research Program.

In NCWF-6, The probability forecast reflects the movement trend, growth, and dissipation of convection. The forecast probabilities, along with forecast storm tops, are provided for certain time intervals (i.e. every hour) 6 hours into the future and are updated every 15 minutes.

3 MODELING APPROACH

We assume that a given airspace is partitioned into cells forming a three-dimensional (3D) grid (work grid). The resolution and the structure of the grid are selected to match the requirements of traffic conflict detection and rerouting algorithms implemented. For the sake of clarity, rectangular two-dimensional (2D) grids are used in this paper. The actual cells could be polygons of any convex shape. Projected time into the future is divided into equal time intervals (work intervals) that match the time horizons of the traffic conflict detection and re-routing algorithms. At any given time interval, each cell has a binary state, i.e. either blocked by weather or not blocked by weather. In the former case, an aircraft can not be routed through the cell; in the latter case, aircraft can be routed through the cell safely.

The modeling process is a mapping from forecast probabilities valid at a sequence of forecast time intervals to traffic blockage maps at a sequence of work time intervals. The mapping process is a Monte Carlo simulation of the stochastic traffic blockage process. Each simulated blockage map sequence is an instantiation of the stochastic process. It is required that as the number of simulated sequences becomes large, the number of instances a cell is blocked at a given time divided by the total number of instance sequences simulated should approach the forecast probability for that cell, at that time interval. Based on this requirement, the simulated ensemble of traffic blockage map sequences would be representative of what would occur, as the number of simulated sequences becomes large.

Depending on the traffic conflict detection and rerouting algorithm design, the work grid structure and the work time intervals for which binary blockage map sequences are simulated may not necessarily be the same as that of the forecast probabilities. Interpolation is thus needed to obtain a sequence of probability matrices that matches the work grid structure and work time interval. The re-sampling of a forecast probability matrix at a work time interval (should a forecast probability matrix already exist at that work time interval) is straightforward. However, the interpolation of forecast probabilities at a work time interval not readily available in the forecast needs careful attention. Feature based image morphing techniques can be used to achieve this objective. This general process is shown in Figure 1.

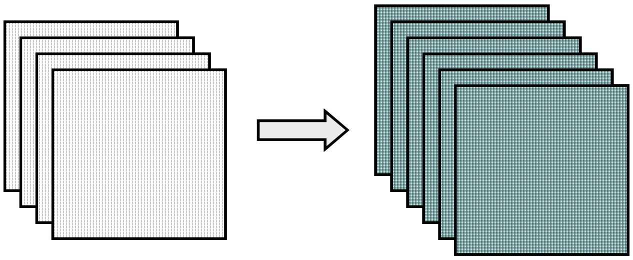


Figure 1: Re-sampling of forecast probabilities

Once a sequence of probability matrices on the work grid and at work time intervals is obtained, the mapping from these continuous probability matrices to binary blockage maps can be performed. This is achieved by passing a band limited 2D random signal (such as a uniformly distributed random signal) defined on the work grid through a shaping filter determined by the sequence of probability matrices. For each of the probability matrices, a corresponding binary cell blockage map is generated as shown in Figure 2. The traffic conflict detection and rerouting algorithms can then be applied based on the sequence of cell blockage maps corresponding to the sequence of probability matrices.

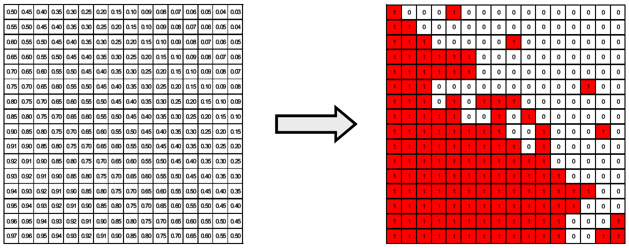


Figure 2: Mapping from a probability matrix to a cell blockage map

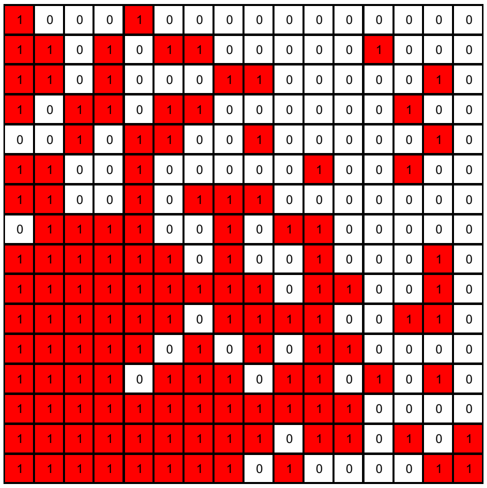
A simple way to do this is to directly map each individual probability value to an individual cell blockage value, i.e. simple random sampling. However, such generated blockage map lacks the spatial correlation between cells (i.e. clustering of blocked cells) and the temporal evolvement between successive cell blockage maps (i.e. continuous trending, growth, and decay of the weather system). Smoothing techniques are applied to the 2D random signal before it is modulated by the probability matrix to generate the blockage map. This is to model the spatial correlation between cells. Cellular Automata are used to model the transition of blockage maps between one time interval and the next. The final blockage map at a given time interval is determined by both the probability matrix at the time interval and the blockage map from the previous time interval. Details of the smoothing techniques and the cellular automata are presented in the next two sections. Various model parameters, such as the smoothing kernel size and the cellular automata rules are obtained from historical convective weather data.

4 SMOOTHING

Suppose a 2D matrix $[\nu_{ij}]$ matching the structure of the grid is generated with its elements being independent random numbers from a uniform distribution on the interval of [0, 1]. An instance of the binary cell blockage map $[b_{ij}]$ at a given time interval can be obtained from the corresponding probability matrix $[p_{ij}]$ for that time interval, and the aforementioned random matrix as

$$b_{ij} = (\nu_{ij} \le p_{ij}) \ . \tag{1}$$

Where a value of 1 for a cell can be interpreted as being blocked, and a value of 0 can be interpreted as not being blocked. For a different matrix of random numbers, a different cell blockage map can be obtained. An example of a cell blockage map for a sample probability matrix is shown in Figure 3.



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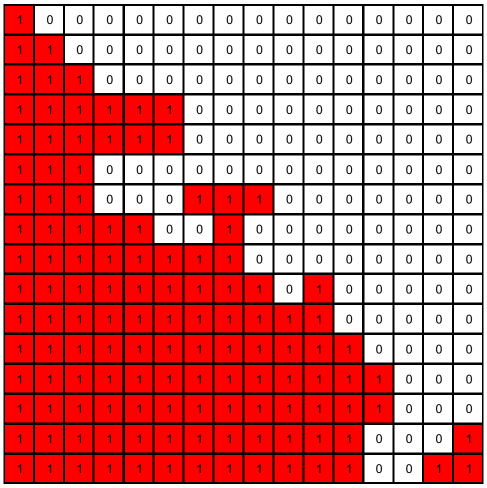
1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1

Figure 3: Sample cell blockage map from direct mapping

By definition, cell blockage maps obtained in this way will preserve the cell blockage probabilities given by the probability matrix. However, as can be seen from Figure 3, the cell blockage map is fragmented because the random numbers used are independent of each other. To model the spatial correlation between cells, Gaussian smoothing is applied to the 2D random matrix before (1) is applied to generate the blockage map. The strength of the spatial correlation can be presented by the Full Width at Half Maximum (FWHM) of the Gaussian kernel. FWHM is related to the standard deviation of the Gaussian kernel by the following equation:

$$\mathrm{FWHM} = \sigma\sqrt{8\ln 2}\,. \tag{2}$$

For the same random number matrix and the same probability matrix, the cell blockage map becomes that shown in Figure 4, when a FWHM of 2 is used. It is seen that the blocked cells are now more clustered. This would more accurately present the blockage cells when a weather system is present.



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1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1

Figure 4: Sample cell blockage map from smoothed mapping

On the other hand, using a fixed FWHM Gaussian kernel across the whole grid may prevent scattered cell blockage in low probability areas. To enable scattered (or popup) cell blockage, adaptive smoothing is used. In this approach, the FWHM of the Gaussian kernel used for each individual cell is dynamically adapted to reflect the varying strength of spatial correlation between cells. Details of the adaptive smoothing approach are described below.

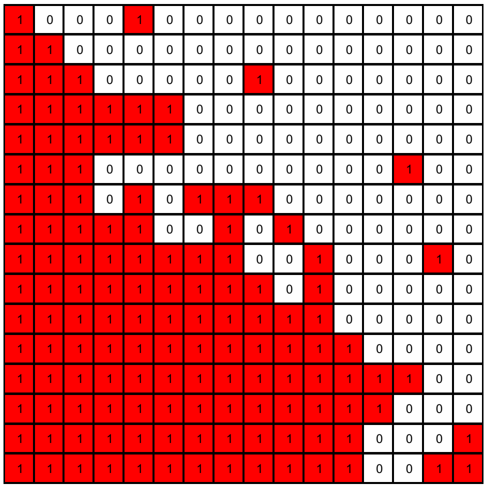
A temporal cell blockage map is obtained via direct mapping without smoothing. The percentage q_{ij} of blocked neighboring cells (including the cell itself) is then calculated for each cell, based on this cell blockage map. The FWHM_{ij} for a cell (i, j) is given by

$$\mathrm{FWHM}_{ij} = f(q_{ij})\,. \tag{3}$$

The size of the neighborhood used in calculating q_{ij}, and the functional relationship between the percentage of blocked neighboring cells and the FWHM in (3) are determined using historical data. In general, for a cell with a higher percent of blocked neighboring cells, a larger FWHM is used to indicate stronger spatial correlation between cells. For a cell with a lower percent of blocked neighboring cells, a smaller FWHM is used to indicate weaker spatial correlation between cells. This would allow retaining scattered blockage, which is not possible by using a single FWHM across the whole grid.

Alternatively, the percentage q_{ij} of blocked neighboring cells can be calculated based on the cell blockage map at the previous time interval. In this case, for a cell with a higher percent of neighboring cells blocked at the previous time interval, a larger FWHM is used. For a cell with a lower percent of neighboring cells blocked at the previous time interval, a smaller FWHM is used. This method is generally used for modeling the popup of isolated cell blockage.

Once the FWHM for each cell is determined, the 2D random matrix is smoothed, and (1) is applied to obtain the cell blockage map. An example of cell blockage map obtained using FWHM values calculated from the temporal cell blockage map is shown in Figure 5.



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1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1

Figure 5: Sample cell blockage map with adaptive smoothing

5 CELLULAR AUTOMATA

As mentioned earlier in this paper, the probability forecasts presented in the form of a sequence of probability matrices provide the movement trend, growth, and dissipation of convection. However, the cell blockage maps independently obtained for different time intervals using the smoothing techniques presented in the previous section may not necessarily form a consistent sequence of cell blockage maps. Difference in the clustering of blocked cells may exist between cell blockage maps at consecutive time intervals. The movement of convection may lag behind or move faster than the trend reflected by the sequence of probability matrices, but the movement of convection should be consistent from one time interval to the next. As in the case of the spatial correlation between cells at any given time interval, the transition between cell blockage maps at consecutive time intervals must also be modeled. Cellular Automata are used for this purpose.

Cellular Automata have been previously used to model discrete dynamical systems. These systems are defined on a grid of cells. Each cell can have any one of a finite number of states at any given time interval. The state of a cell at a time interval is a function of the states of a finite number of its neighboring cells at the previous time interval. Thus, Cellular Automata are suitable tools to model the transition of cell blockage maps from one time interval to the next.

The developed Cellular Automaton does not directly determine the states of cells, i.e. cell blockage maps, but rather, it is used to modify the cell blockage maps obtained using the mapping process presented in the previous section. For each cell, the percentage r_{ij} of blocked neighboring cells at the previous time interval is calculated first. Note that a different symbol is used for the percentage of blocked neighboring cells to signify that both the size of the neighborhood and cell states used in the Cellular Automata implementation may be different from those used for adaptive smoothing. If it is assumed that the cell blockage map obtained using the adaptive smoothing mapping process is $[b'_{ij}]$, then state b_{ij} of each cell at the current time interval is determined by the process shown in Figure 6.

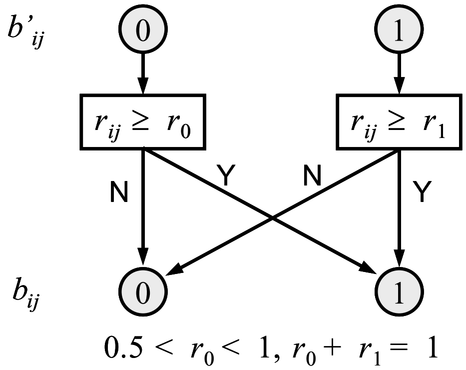


Figure 6: Cellular Automata cell blockage adjustment rules

The transition process shown in the figure implies that the cell state from the mapping process will be accepted as is, if it is in the same state as the majority of its neighboring cells at the previous time interval. The threshold r_0 for converting an unblocked cell from the mapping process to a blocked cell must be greater than 0.5. The threshold r_1 for converting a blocked cell from the mapping process to an unblocked cell must be less than 0.5. The summation of the two thresholds is required to be 1 to ensure the probability of cell blockage is preserved. The transition rules can also be presented in the following equation.

$$b_{ij} = [r_{ij} \ge (1 - b'_{ij}) r_0 + b'_{ij} r_1]. \tag{4}$$

The application of the above process will result in the transition of cell states from one time interval to the next occurring near the boundary of convection. Additional special rules are developed to allow for the popup and growth of scattered blocked cells in low probability areas. Size of neighborhoods and transition thresholds are again determined using historical data.

6 SIMULATION SOFTWARE

A simulation software tool has been developed to simulate traffic blockage due to convective weather. The block diagram of the simulation tool is shown in Figure 7.

The simulation tool takes the forecast probabilities and the initial radar reflection (given for the initial time interval) as input. During the pre-processing phase, the forecast probabilities are re-sampled to give a sequence of probability matrices that matches the work grid and work time interval. The initial radar reflection is processed to obtain an initial cell blockage map. This initial cell blockage map will be used at the start of the simulation loop as the blockage map for the previous time interval. At this time, the simulation is ready to loop through all the work time intervals up to 6 hours, or a different time horizon in the future, should it be desired.

At each time interval, a matrix of random numbers from a uniform distribution on the interval of [0, 1] is generated. This random number matrix is then smoothed using the smoothing method prescribed in Section 4. The probability matrix for the current time interval is then mapped into an intermediate cell blockage map via the smoothed random number matrix. The intermediate cell blockage map is adjusted using the Cellular Automaton mechanism described in Section 5, based on the previous cell blockage map. The final cell blockage map after the adjustment process is then stored for output, and is also used as the previous map for the next time interval.

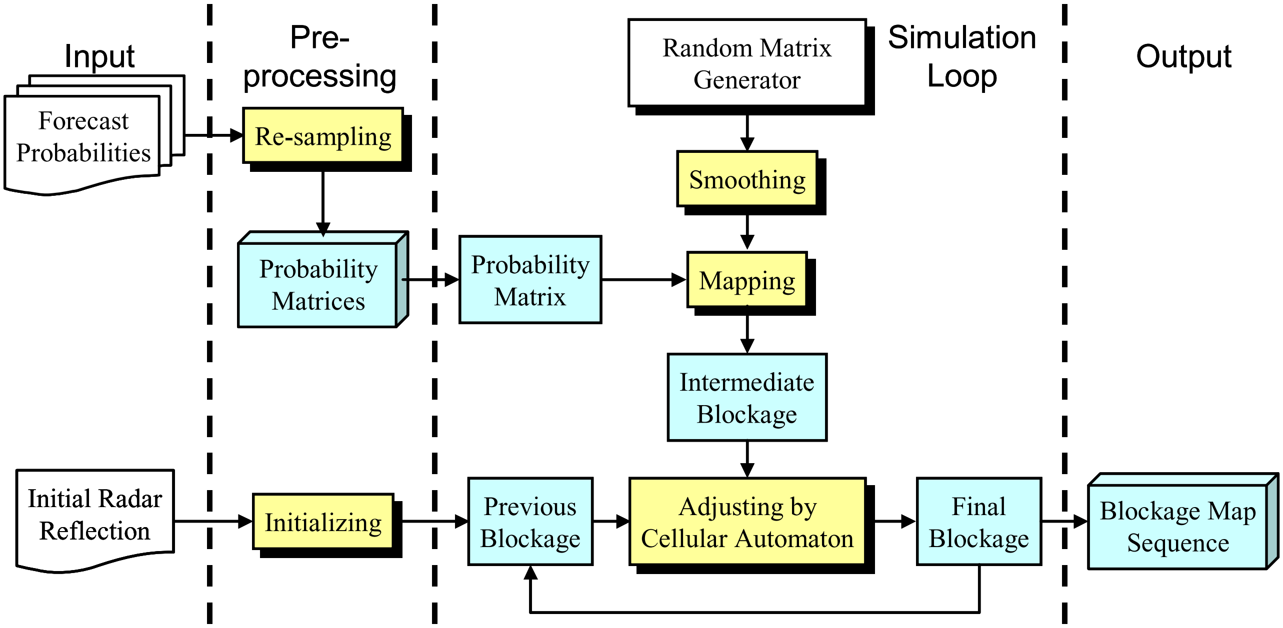
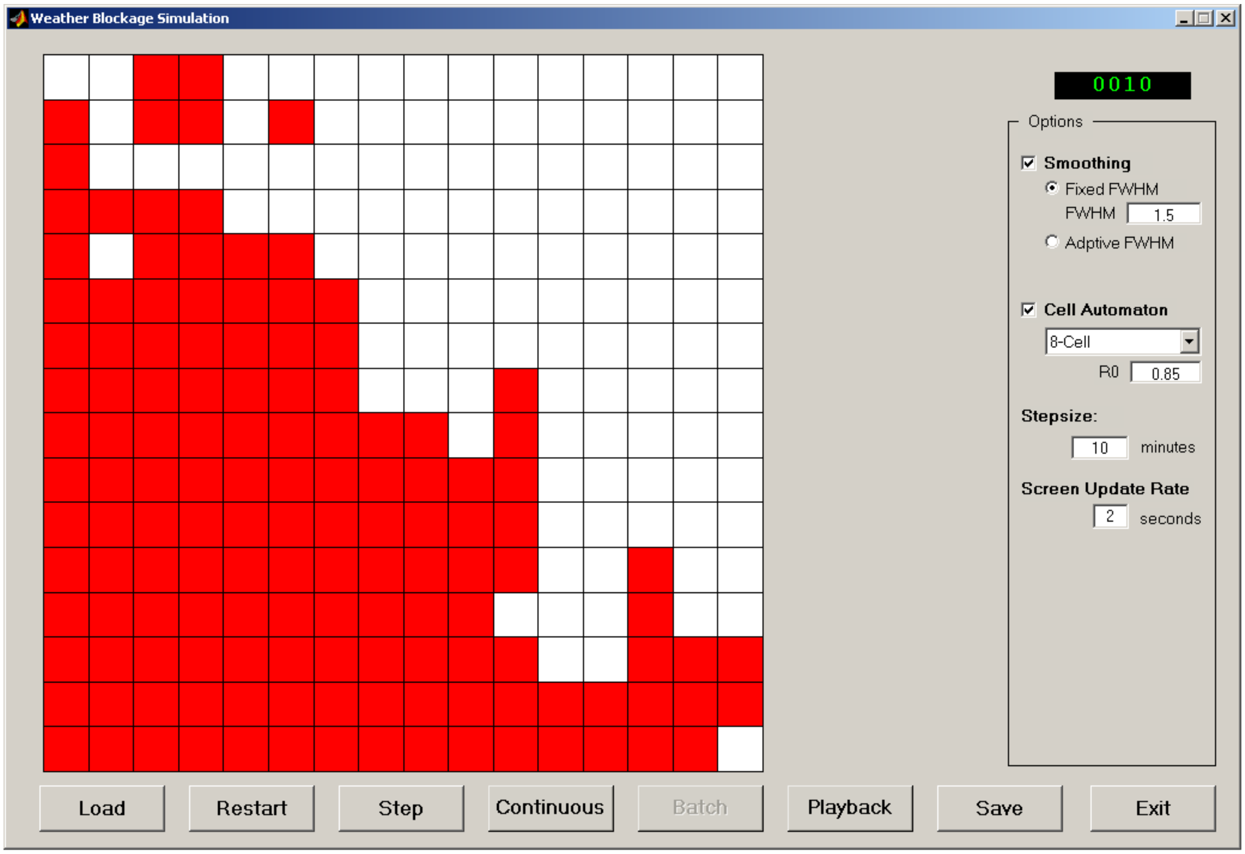


Figure 7: Simulation software block diagram


Weather Blockage Simulation

0010

Options

☑ Smoothing

● Fixed FWHM

FWHM 1.5

○ Adptive FWHM

☑ Cell Automaton

8-Cell

R0 0.85

Stepsize:

10 minutes

Screen Update Rate

2 seconds

Figure 8: Simulation software user interface

After the simulation loop through all the work time intervals, a sequence of cell blockage maps will be obtained. Because of the stochastic nature of the mapping process, if the simulation loop is restarted again, a new sequence of cell blockage maps will be generated. The cell blockage maps can then be used by the traffic conflict detection and re-routing algorithms.

The simulation software is designed to be executed in either command line mode, or interactive mode. The command line mode is useful for operating in-line with the traffic re-routing algorithms. In this mode, simulation parameters are provided in the simulation configuration file, and the simulated sequence of cell blockage maps is saved to a file of choice once a simulation loop is completed. The output file is then ready for use by the traffic re-routing algorithms. The interactive model is useful for debugging the simulation software and adjusting model parameters. It is also useful for demonstration. The user interface of the interactive mode is shown in Figure 8.

In the interactive mode, model parameters can be adjusted by the user interactively via the options panel. The user can manually select the forecast probability file to load. The simulation loop can be executed step by step, i.e. one time interval at a time. It can also be executed continuously until the end. A batch mode is provided to launch automatic execution of the simulation loop as if the simulation is executed in command line mode but it also gives the user ability to adjust model parameters interactively.

The prototype simulation software was developed using the MATLAB Graphical User Interface (GUI) design tool. The final version of the software will be coded in a more portable programming language for easy distribution and application outside the laboratory environment.

7 CONCLUSIONS

We propose a Monte Carlo methodology for simulating air traffic blockage under the impact of convective weather. The simulation methodology can be used to simulate possible weather traffic blockage maps on a grid of cells at a sequence of time intervals given probabilistic convective weather forecasts such as those produced by the 1-6 hour National Convective Weather Forecast. Through a large number of simulation runs, an ensemble of traffic blockage map sequences presenting what could actually happen can be obtained for a given forecast. Various conflict detection and traffic re-routing algorithms can then be applied to these simulated traffic blockage maps. Results can be analyzed to evaluate the efficiency of those algorithms. The simulation methodology thus provides a means to improve the utilization of short term probabilistic convective weather forecast products, and to improve air traffic efficiency in the longer term.

A matrix of random numbers from a uniform distribution on the interval of [0, 1] is fed to the simulation process to obtain an instantiation of traffic blockage maps. Gaussian smoothing with varying Full Width at Half Maximum across the grid is employed to model the varying spatial correlation between cells. Cellular Automata techniques are used to model the evolvement, i.e. the trend, growth, and dissipation of convection, between consecutive time intervals.

A simulation software tool was also developed to realize the proposed simulation methodology. Modeling parameters are being developed using historical convective weather data and the simulation tool is being rigorously tested. Traffic re-routing algorithms are being developed in parallel, and initial computational results suggest the validity of the proposed model.

ACKNOWLEDGMENTS

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