COUPLED ATMOSPHERE-WILDFIRE MODEL FOR PILOTED FLIGHT SIMULATION OF AERIAL FIRE FIGHTING OPERATIONS

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ABSTRACT

A computational model of wildfires has been developed to improve the functionalities of a flight training device developed for the operational training of CL-415 water bomber flight crews. The model, realized in Matlab Simulink, is based on a coupled atmosphere-fire model that is able to simulate the rising plume introduced in the wind pattern by the wildfire depending on the overall wind, temperature, pressure and humidity conditions set by the instructor in terms of ISA and non-ISA conditions in conjunction with MIL-F-8785C windshear model. Actual fire spread and suppression are simulated through the implementation of a cellular automata model fed by a GIS system, while the Coupled Map Lattice (CML) method is used to simulate wind and temperature profiles in the atmosphere block surrounding the wildfire.

Some simplifications have been accepted in order to speed-up the simulation that is run in real-time as a part of the synthetic environment embedded in the flight training device. Good qualitative results have been obtained despite of the simplifications assumed, providing an effective tool to improve the crew perception of fire-related hazards during aerial fire-fighting operations.

INTRODUCTION

Millions of hectares of forestry are destroyed by fire worldwide each year. Firefighting operations are of primary importance in the European Union, especially for those countries facing the Mediterranean Sea, where the combination of densely populated areas, soils characterized by a brush vegetation and low moisture content, elevated temperatures and strong winds during summer cause an ideal scenario for the ignition and propagation of forest fires. As an example, 7,797 fires have been registered only in Italy during the year 2007, with 127,151 hectares of landscape burnt, 61,100 of which being forest (Corpo Forestale dello Stato 2007).

Due to the severity of the threat, aerial firefighting operations represent a significant effort for these countries especially during the summer season, pushing the need for an efficient fleet of large aerial firefighting aircraft in order to guarantee a significant water delivery capability in short time.

As a consequence of this need, several countries employ many different fixed and rotary wing aerial assets with Italy, France, Greece, Croatia and Spain being the major European operators of a well-known amphibious aircraft type specifically designed for the mission of aerial firefighting, namely the Bombardier Model CL-215-6B11 also known as Canadair CL-415.

Figure 1: Canadair CL-415 Operated by SOREM for the Italian Protezione Civile.

Totally, the number of aircraft operated by the five countries in Europe is about 54 (Jane's 2008) but is actually increasing due to several orders on delivery; Italy is actually the major operator with 22 aircraft in active service.

Flying a fire-fighting mission is a hazardous task since many threats are present in the scenario: smoke limits visibility and may cause an engine flame-out or, even worst, an engine fire due to burning leafs and sparks lifted up by the fire-induced buoyancy. If this is not the case, a sensible decay of performance can be expected due to the lower air density in the buoyant plume. Local winds and turbulence may be caused also by the proximity with the terrain (water is delivered usually at 100 ft above ground), that inevitably forces the pilots to fly across strong wind corridors, rotors or other forms of local winds induced by the orography of the terrain.

Due to the above, high skill levels are required to pilots operating water bombers, while at the same time obvious safety considerations preclude effective in-flight training for

specific emergencies (like an engine failure during take-off, water pickup or final water bombing run).
Despite the high number of aircraft and operators involved, actually there are no CL-415 Flight Simulators available in Europe. To fill this gap, Selex-Galileo, with the support of the Regione Autonoma Friuli Venezia Giulia and in partnership with Italian Protezione Civile and SOREM (the company that operates the Italian Canadairs) has developed a demonstrator for a full mission flight simulator specifically devoted to firefighting. The Demonstrator developed so far incorporates a simulation model of the CL-415 aircraft, and a complex simulation of the environment, able to reproduce in real-time the behavior of a forest fire and its associated meteorological phenomena relevant to flight mechanics: local winds, bursts, temperature gradients etc. The simulation of the environment is interactive with the aircraft missions in two ways: the aircraft behaviour is influenced by the perturbations introduced in the atmosphere by the wildfire and the wildfire itself is influenced by the aircraft firefighting action (dropping of water) which affects fire spread on the ground.

Figure 2: Mission Simulator for theCanadair CL-415 developed at Selex-Galileo.

REPRESENTATION OF DISTURBANCES IN FLIGHT SIMULATION

The Flight Simulator is composed by a low fidelity replica of the twin-seat CL-415 cockpit (see Fig. 2). The aircraft instrumentation is emulated on nine touch-screens reproducing the overhead, front and side panels of the aircraft. Handweels (with associated triggers and buttons), pedals, power and propeller throttles and water pickup probes are physically reproduced with an hardware replica of the actual device. Loads on the primary flight controls are reproduced through an electrical control loading system. Aircraft and ambient sounds are reproduced but a motion system is not present. The simulator allows normal aircraft handling, including all normal mission checklists and a limited number of emergencies. Environmental effects are grouped in two major blocks:

- General purpose atmospheric disturbances
- Fire induced atmospheric disturbances.

The first group includes all the atmospheric disturbances generally present in a simulator of this kind modeled according to MIL-F-8785C: steady wind with three different vertical profiles (constant wind, low and high altitude windshear model), atmospheric turbulence (McFarland 1997) is modeled using Dryden spectra tunable in intensity (Light, Moderate, Severe) and type (low and high altitude model); isolated bursts and microbursts models are included.
The second group includes all those disturbances that can be expected in the vicinity of a wildfire and that constitute the specificity of such a simulator. The effect of disturbances is simulated in the aircraft flight mechanics by adding wind-induced translational and rotational velocities to the actual body rates and velocities.

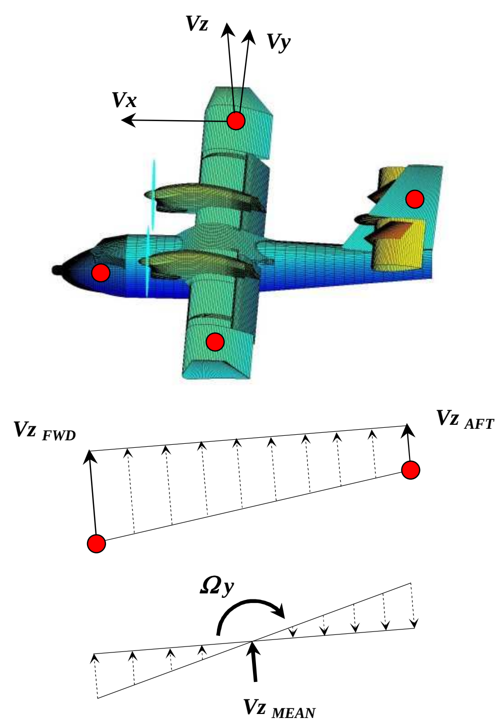


Figure 3: Sampling points for the evaluating wind velocities and decomposition into equivalent mean value and body rate.

The representation of fire-induced disturbances on aircraft behavior is reduced to the calculation of wind velocities along the aircraft flight path at the four evaluation points (See Fig. 3). This is accomplished by interpolation of wind velocities over a spatial grid covering a square domain surrounding the wildfire area; wind velocities are updated in real-time according to the evolution of the coupled fire-atmosphere model.

COUPLED WILDFIRE-ATMOSPHERE MODEL

The idea at the basis of a coupled fire-atmosphere model is to catch the main interactions between the two physical phenomena that are:

- Fire releases heat in the atmosphere causing a buoyant plume; mass conservation produces diffused areas of entrainement at the plume edges.
- The wind pattern on ground is influenced by the areas of entrainment, thus influencing the fire spread.

Coupled wildfire-atmosphere models are often employed in simulations devoted to emergency management (Coen 2003, 2005 and Coen et al. 2006); generally the approach is to couple a fire spread algorithm like FARSITE or BEHAVE to an atmosphere simulation package of the same type of those commonly used for meteorological forecasts like WRF (Patton & Coen 2004).
Figure 4 illustrates schematically the interactions between the aircraft, fire and atmosphere models. Pseudocolors indicates a wind speed in excess (red) or defect (blue) of the far field condition.

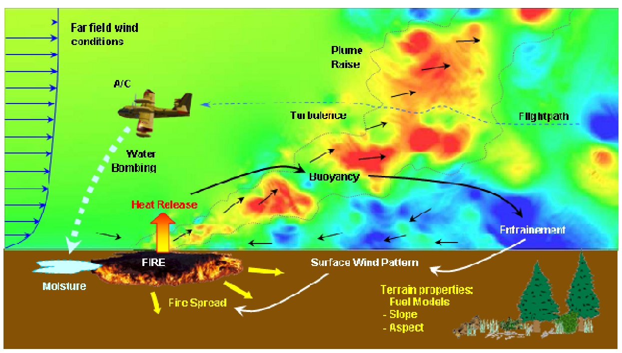


Figure 4: Conceptual sketch illustrating Fire-Atmosphere-Aircraft mutual influences.

The peculiarities of the application to a flight simulation of an aerial firefighter are:

- The spatial discretization of the atmosphere computational grid should be such that small scale phenomena can be resolved to allow proper simulation of aircraft motion through the disturbances.
- The spatial resolution of the wildfire computational grid should be such that the firefighting action (pouring water into the fire) can be effectively resolved reproducing the effects of slope, drop altitude, aircraft speed etc.
- The execution times of the fire and atmosphere models should be such that real-time execution can be performed.

Fire spread on the ground is affected by “static” terrain properties (fuel models, slope, aspect) but also by dynamic quantities as the induced wind and the water drops..

Fire Spread Model

The simulation spread model is based on the implementation of cellular automata algorithm using a set of mathematical equations developed in C language (derived from the BEHAVE model) and imported in the Simulink environment. BEHAVE is a fire behavior prediction system developed in early 80’s. It allows predicting a set of fire features such as rate of spread and fire intensity using 13 types of terrain model and different weather conditions as required in the Rothermel model (Rothermel 1972).
The fire behavior is modeled starting from two-dimensional square grids derived from a GIS system: it can be represented as several different layers where each layer holds data about a particular kind of feature.

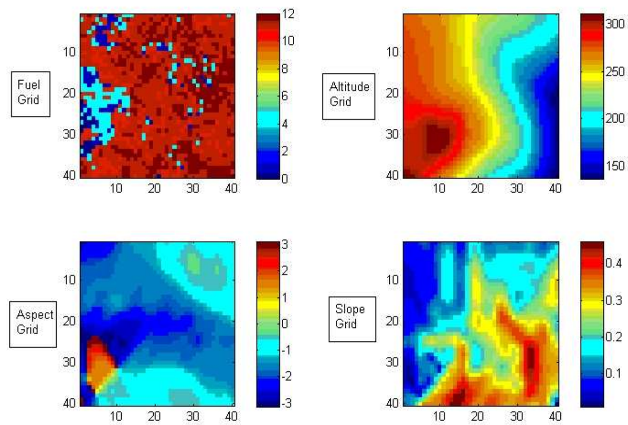


Figure 5: 40 x 40 grid types obtained from GIS data.

In particular, the simulation model requires as input:

- Fuel Models
- Terrain Slope
- Terrain Aspect

Fuel Models consist of 13 different type of terrain, used by Albini (1976) including 11 developed by Anderson and Brown and published by Rothermel (1972).
Slope is the change in elevation with respect to change in horizontal position. In our case, slope gives the maximum rate of change between each cell and its neighbors.
Aspect is the direction of the plane with respect to some arbitrary zero (north). The value of each cell indicates the direction the cell's slope faces.
User can choose the initial ignition point/points of the considered map by setting an input properly. Fire algorithm will consider this point/points as burning starting from next simulation time step. One or more ignition points can be added during simulation.
From these data it is possible to calculate the time required for a fire to travel from a burning cell to one of the adjacent eight cells under particular weather conditions (moisture, wind speed and wind direction). Fire propagation from cell to neighbor cells is computed by Rothermel equations according to the speed and direction of the local wind,

remaining fuel in the cells and elapsed time since the fire broke out.

The model also takes care of simulation bonds such as time-step and a-synchronous inputs (eventually) coming from other systems, such as moisture growing effects due to water bombing actions.

At each step, the algorithm loops on the entire grid and assigns for each cell an ignition time, depending on the simulation inputs. If the next ignition time (TimeNext) is less than the current simulation time, eight ignition time values (corresponding to the eight neighbors) for each burning cell are provided and the next TimeNext value is calculated. A cell starts burning when its ignition time is less or equal to TimeNext. See Figure 7 for an example of burning cell sequence under constant environment condition.

The flow chart of the spread algorithm is shown in Figure 6.

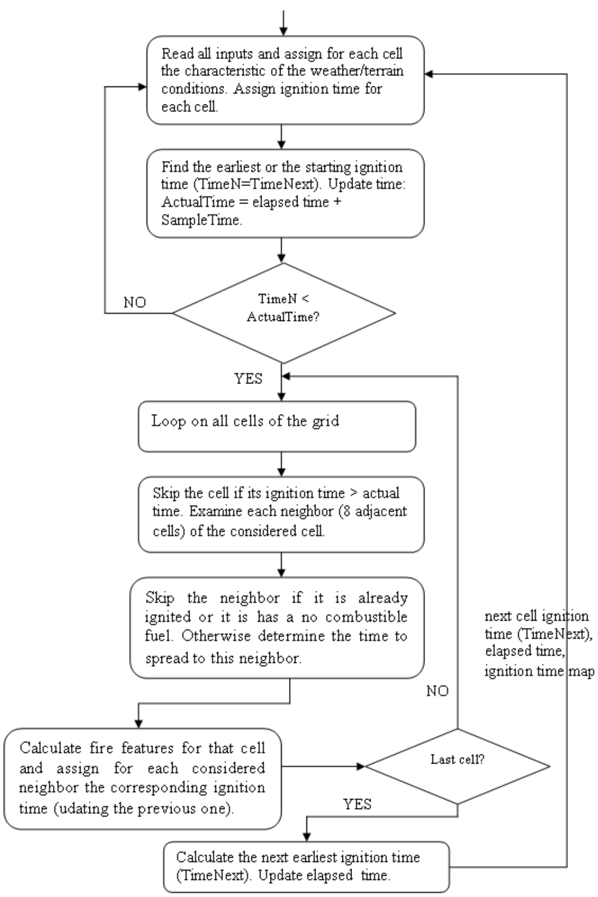


Figure 6: Flow chart of fire spread algorithm.

Moreover, an interface has been developed in Simulink in order to observe some simulation constraints (for example: the interfacing with other systems) and to avoid that a burned cell could start burning again.

Fire properties (i.e. Reaction Intensity, Flame Height, etc.) are calculated at each simulation step through the C library: it contains BEHAVE fire behavior algorithms, encapsulated and optimized for fire behavior simulation.

Access to library is performed via C macros that are used like C function calls to access or update current object properties.

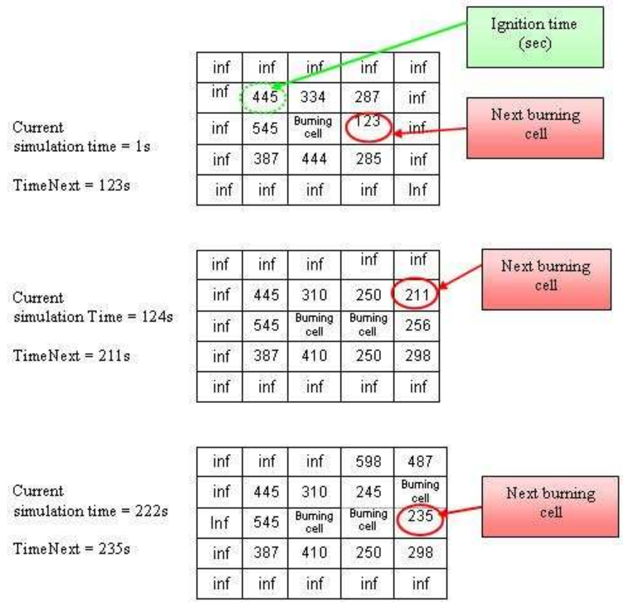


Figure 7: Cells burning sequence under constant environment conditions.

Atmosphere Model

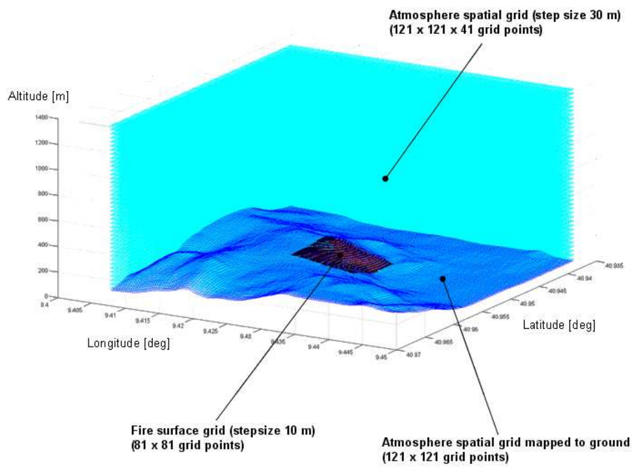
The dynamic simulation of the atmosphere in the vicinity of the wildfire is based on the Coupled Map Lattice (CML) method. The CML is a simplified numerical method for the solution of non linear equations originally proposed by Kaneko (Kaneko 1990). An efficient computational method based on CML for the solution of fluid equations was proposed by J. Stam (Stam 1999) with application to the visual simulation of smoke. CML have been used extensively to simulate fluid motions, especially for real-time computer graphics, since its implementation on graphic hardware considerably speeds up the calculation and rendering times (Crane et al.2007, Wu et al. 2004). The implementation we adopted is based on some works related to cloud dynamics (Mizuno et al. 2002, Miyazaki et al. 2002, 2001, Dobashi et al. 2000).

To simulate the fluid flow, the atmosphere is approximated as an incompressible viscous fluid, thus denoting the velocity vector as **v**, the pressure as p and the density as ρ the full Navier-Stokes equations can be reduced to a form like:

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\,grad(p) + \nu\Delta\mathbf{v} \qquad (1)$$
$$div(\mathbf{v}) = 0$$

The second equation above is the “continuity equation”, expressing conservation of mass, while the term $D\mathbf{v}/Dt$ is a material derivative operator.

To solve equation (1), the atmosphere surrounding the wildfire is discretized using a cartesian spatial mesh adapted to the ground surface and extending several hundreds of meters on the sides and above the fire surface grid (Fig. 8).
The spatial discretization is an odd multiple of the fire discretization, allowing each atmosphere grid point to “cluster” several fire grid points.
Physical quantities are defined at each grid point in terms of wind speed, air temperature, pressure and density. All these quantities are initialized at the first step using the environmental conditions set from IOS (Instructor Operating Station) outside of the domain. Dirichlet boundary conditions assure continuity of the physical variables during the simulation as the aircraft crosses the domain boundaries.



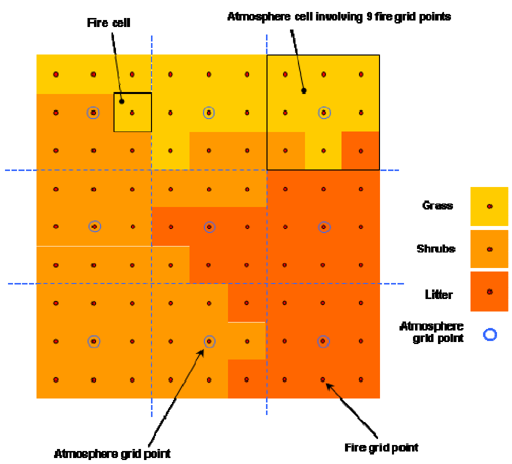


Figure 8: Atmosphere and fire grids.

The dynamic evolution of the physical quantities is calculated by successively applying operators reproducing the phenomena represented by the different terms in equation (1) which are:

- Viscosity and pressure effects
- Advection of state variables by the fluid flow
- Thermal diffusion
- Thermal buoyancy

Each operator is defined as follows.

Viscosity and pressure effects.
Viscosity causes velocity diffusion while pressure gradients drive the velocity field. Instead of introducing explicitly the pressure as a state variable in the calculations, we followed the approach of Miyazaki (Miyazaki et al. 2001) introducing the discrete version of *grad(div(***v***))*.
Following the notation of Miyazaki, let’s denote as v_x the x-component of velocity at the current time step at the grid point with indices i,j,k and v_x^* the same component updated by the viscosity and pressure operator (the y and z components are calculated in the same way with permutations of the indices):

$$v_x^*(i,j,k) = v_x(i,j,k) + k_v \Delta v_x(i,j,k) + k_p\, grad(div\mathbf{v})_x \qquad (2)$$

Where k_v is the viscosity ration and k_p is the coefficient of the pressure effect. The second and third terms above are:

$$\begin{aligned}\Delta v_x(i,j,k) = \frac{1}{6}[&v_x(i+1,j,k) + v_x(i-1,j,k) + \\ &v_x(i,j+1,k) + v_x(i,j-1,k) + \\ &v_x(i,j,k+1) + v_x(i,j,k-1) - 6v_x(i,j,k)]\end{aligned} \qquad (3)$$

$$\begin{aligned}grad(div\mathbf{v})_x = &\frac{1}{2}[v_x(i+1,j,k) - 2v_x(i,j,k) + v_x(i-1,j,k)] + \\ &\frac{1}{4}[v_y(i+1,j+1,k) + v_y(i-1,j-1,k) \\ &-v_y(i-1,j+1,k) - v_y(i+1,j-1,k) \\ &+v_z(i+1,j,k+1) + v_z(i-1,j,k-1) \\ &-v_z(i-1,j,k+1) - v_z(i+1,j,k-1)].\end{aligned} \qquad (4)$$

Advection by the fluid flow.
Advection is incorporated as originally proposed by Stam (Stam 1999) and successively by Miyazaki (Miyazaki et al. 2001) by back-propagating the state variables with the current values of velocities at grid point *i,j,k* and interpolating over the whole 3-D mesh to get the advected value. Even if this method is reported to be unconditionally stable we found that stability problems can occur due to the strong gradients in proximity of the ground if large time steps are adopted. Stability problems have been addressed in a very straightforward way by limiting the maximum wind speed to values consistent with the spatial and temporal discretization.

Thermal diffusion.
Thermal diffusion is accounted for by an operator identical to equation (3) above applied to the temperature field with a constant k_d.

Buoyancy.
Buoyancy is accounted for by adding a vertical velocity at each grid point proportional to the difference between the actual value of temperature at the grid point and a “reference” value (assumed to be the undisturbed atmosphere temperature at that altitude). The coefficient of proportionality is made itself a linear function of altitude

going to zero at a prescribed altitude; this forces the plume shape to be nearly horizontal at the desired altitude and allows a more robust simulation.
This simplification doesn't practically impinge the realism of the simulation, as it is felt by the pilot, since firefighting operations usually happens at low altitude and in the vicinity of the fireline, where strongest gradients exist.

Other simplifications.
Several simplifications have been adopted in order to reduce the complexity of the problem and speed up calculations:

- Grid stretching in the vertical direction is not accounted for; this assumption is valid as long as the ground surface is sufficiently "flat" with respect to the grid size.
- The vertical profile of pressure is assumed to remain fixed during the simulation (say an ISA profile); density variations are consequently only due to changes in temperature.
- Wind is initialized with a MIL-F-8785C profile depending only on height above terrain and not taking into account the local orography.

As a fire grows on the ground, the heat released by the burring cells is transferred to the atmosphere grid points by collecting the contributes of all the cells in a cluster. Heat release causes a rise of temperature at the atmosphere grid point, forcing convection through buoyancy and mass conservation but causing also diffusion and advection to the adjacent grid points.
The wind pattern calculated using the CML is fed back to the wildfire model by interpolating wind velocities on the ground; this process closes the interaction between the two models.

DETAILS OF THE SIMULINK IMPLEMENTATION AND COMPUTATIONAL CONSIDERATIONS

The Fire Simulator basically consists of a Simulink model that implements:

- The fire spread algorithm, written in C code.
- A library, based on BEHAVE system, for predicting spread rate and reaction intensity of wildfires.
- A set of interfaces and optimizations in order to run the simulation in real time mode and to prevent some possible not physical behavior during the simulation execution.

C codes are integrated into the simulink model through the Matlab *Legacy Code Tool*: this method generates a Matlab type dll (*.mexw32) that can be included in the Simulink model.
Fire simulation has to be coupled with Atmosphere simulation to obtain a single Simulink model (.mdl).
Basically, there are two simulation environments: a Simulink stand alone simulation, that runs on a workstation, and the actual Flight Simulator software residing in the host computer, coded in C language. The Matlab Simulink model is ported in C language using the Real Time Workshop Embedded Coder, a Mathworks product that generates compact and fast stand-alone C code.
It is important to underline that the coupled Fire-Atmosphere simulation requires high CPU resources as the grids increases in dimensions, so Multithreading and/or Multitasking techniques should be heavily used during both modeling and code generation phases.
The following figure shows how the two models are coupled in Simulink:

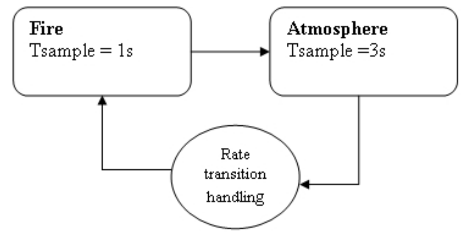


Figure 9: Fire - Atmosphere interaction in Simulink

In order to manage the different sampling rate of the two models, a rate transition block is introduced between them.
In the "General Multithreading Preferences" of Matlab environment, Multitasking option must be enabled.
This setting permits an implicit multithreaded computation that speeds up element wise computations such as those done by the sin and log functions, and computations that use the Basic Linear Algebra Subroutines (BLAS) library, such as matrix multiply. However not all functions in MATLAB are multithreaded, moreover Matlab will never be able to determine if, for example, consecutive function calls in a for-loop are independent of each other.
More complex is to generate optimized code for multithreading, because with the "standard" Real Time Workshop is not possible to generate code optimized for multithread application.
However the multirate model permits to perform some optimizations, starting from the multitasking option that must be enabled on Simulink tasking mode preferences. This setting reflects on the code generation: two main step functions are created (Step0 and Step1).
The final code run on multiprocessor workstations, so the two step functions can be associated with two separate threads (or tasks) running on two separate CPUs.
CPU load on executing Fire model is in the order of 3%. The main algorithm is entirely executed in a scheduler clock cycle (1Hz).
Atmosphere simulation requires a lot of CPU resources, so it is a requisite the all Atmosphere calculations terminate at the next Atmosphere scheduler timing. To ensure that this constraint is satisfied, the Atmosphere task is scheduled at a lower rate (0.33 Hz) than the Fire task.

VERIFICATION AND VALIDATION

The simulation reported in figure 10 is based on the following input:

- Fire grid: 63 x 63 matrix, each cell with area 100 m^2.
- Atmosphere 3D grid: 101 x 101 x 31, stepsize 30 m.

Terrain altitude, slope, aspect, and type are extracted from GIS data and constitute the terrain inputs data for the simulation. The area of interest is a wood in the Maddalena Island, with high density of shrub.
From three ignition cells, fire propagates burning 5.5ha of forest (terrain type: 11 and 12) in about 1h 30min. Fires are ignited under moderate weather conditions: wind was about 3.5 m/s and the terrain characteristics unfavorable for the fire spread (wind blows downhill) leading to a medium fire size in relationship with the elapsed time. By contrast, large catastrophic wildfires are usually driven by severe fire weather conditions with high wind speeds. Note that fire can even propagate to the other side of the road.

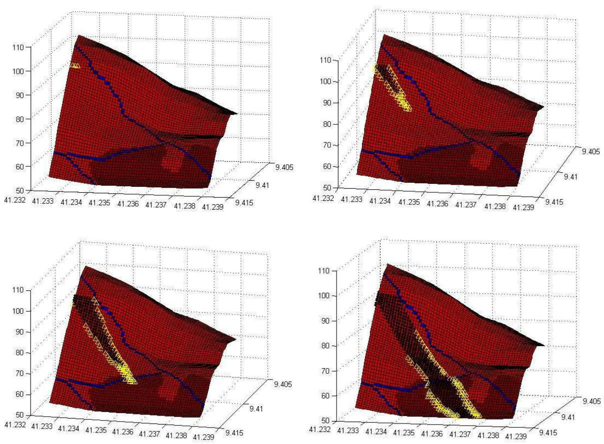


Figure 10: Fire evolution from time 0s to time 5400s.

Simulation results depend on a lot of parameters. Fire shapes simulation on the same terrain can vary significantly simply changing the atmosphere conditions (i.e. wind, moisture), for example winds blowing in direction of rising terrains that hugely favor the fire spread.
A good mean of validation of fire evolution in Maddalena island and neighboring zones, is based on statistically observations of Sardinia fires evolution in the past years. Using the sequence of daily values of fuel moisture and wind, it possible to reproduce fire spread and fire effects with limitations and assumptions of Rothermel's model on the simulation accuracy, described in Andrews (1986).

The following figures show the output of the atmosphere simulation when the fire is completely developed.
The buoyant plume can be clearly identified in Figure 11: the red dot indicates the maximum vertical velocity value of 6.023 m/s. The combined effect of diffusion and advection propagates velocity and temperature downstream of the fire location; the maximum air temperature is 353 K (80 °C) and is located on in the vicinity of the flame core. The flow looks quite viscous since smaller vertical flow structures are absent. Experiments have been conduced introducing Perlin noise or vorticity confinement techniques but this was found to increase significantly the computation time without appreciable effects felt by the pilot. The technique finally adopted to introduce some randomness in the velocity distribution is to keep the atmospheric turbulence active and switch the intensity level according to the velocity gradients encountered by the aircraft.
Figure 12 shows the ground wind pattern in the area of the fire front (about 3.5 m/s wind coming from left in the figure) showing the local wind speed in pseudocolors; the entrainment effect is clearly visible through the convergence of the velocity vectors and the local increase in velocity magnitude.

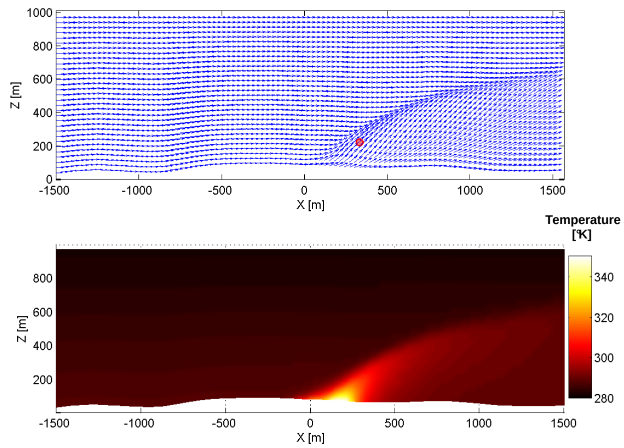


Figure 11: Wind and Temperature distribution in the atmosphere grid.

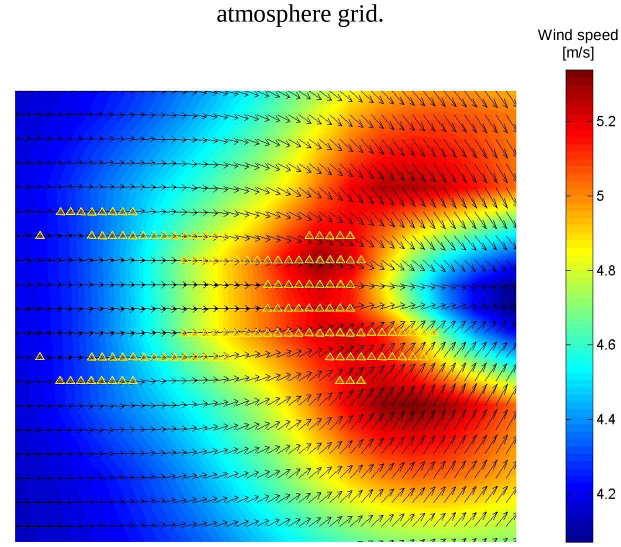


Figure 12: Local wind pattern on ground showing entrainment effect.

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BIOGRAPHY

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