Approaching Urban Disaster Reality: The ResQ Firesimulator

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Abstract. The RoboCupRescue Simulation project aims at simulating large-scale disasters in order to explore coordination strategies for real-life rescue missions. This can only be achieved if the simulation itself is as close to reality as possible. In this paper, we present a new fire simulator based on a realistic physical model of heat development and heat transport in urban fires. It allows to simulate three different ways of heat transport (radiation, convection, direct transport) and the influence of wind. The protective effects of spraying water on non-burning buildings is also simulated, thus allowing for more strategic and precautionary behavior of rescue agents. Our experiments showed the simulator to create realistic fire propagations both with and without influence of fire brigade agents.

1 Introduction

The RoboCupRescue Simulation League aims at simulating large scale disasters and exploring new ways for the autonomous coordination of rescue teams [2]. These goals are socially highly significant and feature challenges unknown to other RoboCup leagues, like long-term planning of rescue missions involving heterogenous agents. Moreover, the environment these agents act in is a large-scale simulation which is both highly dynamic and only partially observable by a single agent.

It is due to the latter features of the environment that real disaster situations seldomly can be predicted and, in turn, are often not adequately dealt with when they actually occur. Therefore, it must be one of the main goals of the RoboCupRescue Simulation League to develop realistic disaster simulators that allow agents to develop realistic mission plans. In this paper, we describe a new fire simulator that progresses towards this goal while not exceeding the run-time limitations of the RoboCupRescue simulation system. Previous approaches to firesimulation outside the RoboCupRescue domain are reviewed in an extended version of this paper [4].

The RoboCupRescue simulation system is a modular framework based on a Geographic Information System (GIS) describing a city map, and a kernel which acts as a communication hub and integrator of changes to the world model as proposed by the various agents and simulators connected to the kernel. (In the extended paper [4] we describe a direct communication interface for simulators that allows to share internal physical data and thus to model complex interactions, like fire causing the collapse of a house, without overloading the kernel communication channels).

Some of the new features of the introduced simulator are the calculation of heat development in burning houses as well as the simulation of three significant ways of

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heat transportation *between* buildings. Especially, the influence of wind on the spread of fire is taken into account. Another step towards greater realism is achieved by the possibility to limit fire spread by “preemptive extinguishment”, i.e. the spraying of water on non-burning buildings in order to temporarily protect them from catching fire. These new features do not only add to the realism of the simulation, but will also allow rescue agents to act more strategically and precautionary than before. Interacting with an adequate earthquake/collapse simulator, even the starting of fires can be simulated without need for artifical “ignition points” as used in the current simulation, hence supporting the automated generation of realistic disaster situations of variying difficulty.

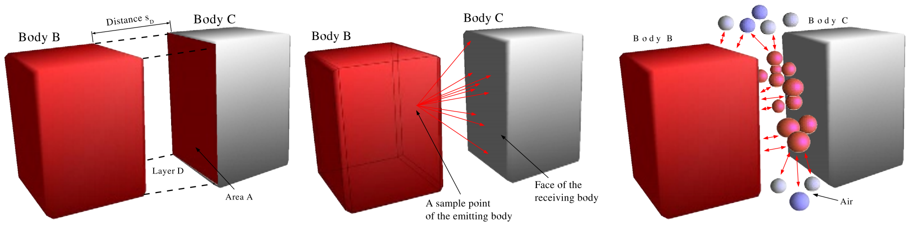
The remainder of this paper is structured as follows. Section 2 introduces the physical theory underlying the simulation, whereas section 3 describes its implementation. Section 4 demonstrates some of the new features of the simulator and section 5 provides an outlook to further developments.

2 Fire Simulation

2.1 Physical Theory

Since fire produces and is ignited by heat, we have to familiarise our self’s with heat and heat transportation. The following paragraph presents simplified relations, for more detail see the extendet version of this paper [4].

The temperature of an object is a measurement for the inherent heat energy depending on the objects heat capacity. The heat capacity describes the change of temperature in dependency from the energy change. Whenever two objects with different temperatures are joined, heat energy is transported from the warmer to the colder (figure 1a). The amount of transfered energy is proportional to the temperature difference and the exposition duration. This effect is called *direct transport*. Objects are emitting respectively receiving heat energy even when they are not directly connected. Objects are emitting *heat radiation* in dependency from there temperature, which is nothing else then light, typically in the infrared spectrum and hence energy. Other objects sharing a line of sight with the emitter are receiving a part of this energy, depending on the distance and the size



(a) (b) (c)

Fig. 1. Three ways of heat transportation: *direct heat transport* (a), two bodies (B and C) exchanging heat by area A, *radiation* (b), the receiver absorbs the energy from beams hitting it’s surface and *convection* (c), heat is transported by air. (The more complex distance and layer computations shown in fig. (a) are described in the extended paper [4])

of the exposed areas (figure 1b). A third kind of heat transportation, called *convection*, can take place within gases. When a region of gas is warmed up its volume increases and therefore its mass density decreases. The result is an ascending of warmer volumes while colder descend(figure 1b).

3 Implementation

Due to practical reasons, the amount of computing power in the RoboCupRescue League is limited on both the server and the client side. Each simulation connecting to the kernel has to finish all calculations and network communication within a discrete time step of 500 milliseconds. Therefore efficient algorithms are a necessary requirement. Particularly, if simulators mutually depend on the results of their calculations, the worst case cost must never exceed the given time constraint. Computational complexity of a simulation is usually reduced by an appropriate discretization of the world. In the RoboCupRescue domain the discretization is already given by the level of detail of the provided GIS data. This data is distributed in entities, such as buildings, streets and civilians (of which currently only buildings are relevant for the fire simulation). Buildings are defined by a polygon describing their footprint, the number of floors, the area at ground level as well as the type of construction, i. e. steel frame, reinforced concrete or wood. As global properties, the wind direction and speed are provided [3]. Since this model does not suffice for the simulation of all physical effects, the simulator additionally implements a discrete model of the air temperature, that will be described in the subsequent section.

3.1 Discrete Model

The high complexity of urban fires, i.e. due to unpredictable air streams and an inhomogeneous distribution of fuel, can only be simulated with strong restrictions. Complex gas flux calculations are beyond question as well as air-flow pattern computation considering the influence of buildings. We restricted the model to two dimensions, like the rescue domain itself. The O_2 concentration level is assumed as constant and as sufficiently available for combustion.

The simulation of **heat radiation** is carried out by an efficient approximation. If the total amount of heat energy emitted by radiation from one building to another is known, a simple and fast to process equation can be used:

$$T_j(t+1) = T_j(t) + \left(-radiation(j) + \sum_{i \in B, i \neq j} p_{i,j} \cdot radiation(i) \right) \cdot \frac{\Delta t}{\Gamma_j} \qquad (1)$$

where $T_j(t)$ is the temperature of building j, $p_{i,j}$ the percentage of radiation from building i that contributes to j, Γ_j the heat capacity of j, and Δt is the duration of a time step in the simulated world. Table 1 provides reasonable values of mass densities, whereas the specific heat capacity values for different construction types are currently set by the user in the configuration file. From these values the building specific heat capacity Γ_j is calculated.

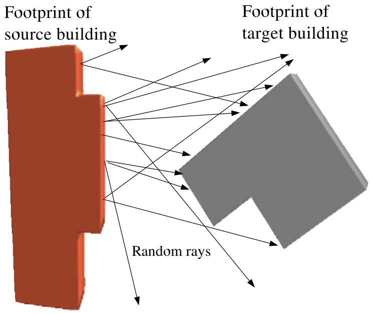


Fig. 2. Randomly emitted rays: The percentage of rays hitting the target building determines the amount of transfered energy by radiation

Equation 1 is based on the assumption that the temperature is constant during a simulation interval and that transportation takes place only between cycles. The value of each $p_{i,j}$ is not calculated completely but randomly sampled with a Monte Carlo method. Each building is broken down into its outer walls as they are provided by the GIS. For each wall a number of random rays originating from this wall are generated. The percentage of rays emitted from building i that hit building j is taken as a stochastic approximation for $p_{i,j}$ (see figure 2). Since the mapping of $p_{i,j}$ is assumed to be constant, these calculations are done offline during the simulation start-up. To enhance the performance, a few improvements have been implemented. The $p_{i,j}$ data for the loaded map is written to hard disc and linked with a hash code that is calculated from the building's unique longitude and latitude. Buildings with a distance exceeding a threshold, which can be set in the configuration file, are left out of the calculation. The expected error from this simplification is comparably low, since the energy density from a point source at distance r is proportional to $\frac{1}{r^2}$ and thus negligible. The radiation function $radiation(i)$ is calculated utilising the Stefan-Boltzmann-Law.

The simulation of **direct heat transport** and **convection** is limited to a single layer situated above the ground. Higher layers are ignored because we assume them to have a small effect regarding the emitting building. The layer is implemented by a two dimensional grid that discretizes the air's continuous heat distribution. The resolution of the grid is currently set to five meters, but may be set differently in the config file of the simulator. The standard ambient temperature is 20° Celsius which is the initial default value for all cells.

The update of a the temperature $s_i(t)$ of air cell i with respect to set of cells R within the air transmission range of cell i, and buildings B_i intersecting with cell i, is calculated by:

$$s_i(t+1) = s_i(t) + \left(\frac{\sum\limits_{j \in R, j \neq i} s_j(t) \cdot w_{i,j} + \sum\limits_{u \in B_i} T_u(t) \cdot a_{u,i}}{\sum\limits_{j \in R, j \neq i} w_{i,j} + \sum\limits_{u \in B_i} a_{u,i}} - s_i(t) \right) \cdot l_a \cdot \Delta t \quad (2)$$

Table 1. Typical energy release rates for city buildings taken from Chandler's investigation [1]. N denotes the number of floors in a building

Type of Fuel	Fuel Load (GJ/hectare)	Mass Density (Kg/hectare)
Dwellings, offices, schools	3,700-9,400	202,000-504,000
Apartments	8,900 $\cdot N$	490,000 $\cdot N$
Shops	9,400-18,800	500,000-1,010,000
Industrial & Storage	5,700-57,000 or more	300,000-3,000,000 or more

where $w_{i,j}$ weighs the temperature influence on cell i from surrounding cells according to their distance, $a_{u,i}$ weighs the influence of buildings B_i intersecting with air cell i, $T_u(t)$ is the temperature of building u and l_a is the heat exchange coefficient. In order to keep the original temperature values from time step t in memory, the implementation of formula 2 is carried out by employing two arrays that are swapped after each update.

Besides the air-to-air and building-to-air temperature exchange, also the air-to-building exchange has to be considered. Therefore an equation similar to equation 2 is introduced that accounts for the different heat capacities of buildings:

$$T_u(t+1) = T_u(t) + \left(\frac{\sum\limits_{i \in S_u} s_i(t) \cdot a_{u,i}}{\sum\limits_{i \in S_u} a_{u,i}} - T_u(t) \right) \cdot \frac{l_b \cdot \Delta t}{\Gamma_u} \tag{3}$$

where $T_u(t)$ is the temperature of building u, Γ_u is the heat capacity of u, l_b is the heat exchange coefficient and S_u is the set of all air cells intersecting with u.

Furthermore every air cell loses heat to the atmosphere due to convection. The amount of heat loss for each cell $s_i(t)$ is approximated by:

$$s_i(t+1) = T_0 + (s_i(t) - T_0) \cdot c_{loss} \Delta t \tag{4}$$

where T_0 denotes the ambient temperature and c_{loss} is a constant approximating a realistic average degree of heat loss.

The effect of global wind is simulated by shifting air cells accordingly to wind velocity and direction on the grid. However, since it is possible that the newly calculated position will not match the grid discretization, grid values, intersecting the shifted cell, have to be recalculated accordingly. The new value of a grid cell is calculated from the weighted average of all cells overlapping due to the shift.

Every building with a temperature above the ignition point and sufficient fuel is considered as burning. Then, during each cycle, a certain percentage of its initial fuel is transformed to energy and added to the building's energy value. Empirical data of fuel densities, as presented in table 1, is utilized for the calculation of the initial fuel values.

3.2 Extinguishing Fires

The action *extinguish building* in the RoboCupRescue domain is realized, for both extinguishing and preemptive extinguishing, by increasing an internal value for each building that represents the amount of water used on it by fire brigades. The fire simulator ensures that all necessary preconditions for this action are met, which are a sufficient amount of water in the fire brigade's tank, a position close enough to the fire and a maximum amount of water that may be emitted per round.

From the amount of water in a building a fraction, linearly proportional to the temperature of the building, is considered to be vaporizing and by this cooling the building during each cycle. The heat energy reduction is calculated by the product of the amount of vaporizing water and its vaporization constant.

Like in reality, preemptive cooling will protect buildings from catching fire temporarily but will not make them completely fire-proof as long as surrounding houses are burning. Thus, preemptive extinguishment offers new strategic possibilities for fire brigades but does not relieve them of the duty to stop fires completely.

4 Experiments

Due to the fact that real data of urban fires is hardly available and if so, is specific to a particular fuel distribution and wind, a close-to-reality evaluation seems to be impossible. Therefore we present a visualization of the new fire simulator's general behavior and compare it to that of the old one. In comparison to the old simulator, which tends to create a circular wall of fire, the new simulator spreads fire in a more realistic way (see figure 3). The dynamic fire propagation matches the complex behavior of real urban fires. As shown in figure 3, the fire spread of the new simulator depends on the density of buildings situated in the area. A high density of buildings leads to a rapid fire spread, whereas larger open spaces behave as fire barriers. The new feature allows fire brigades to predict the most likely fire spread by reasoning about the fire danger of certain districts. Prediction makes it possible to concentrate forces on jeopardized locations and to naturally exploit open spaces. For competitions, the fire barrier effect is not always wanted since an unextinguished fire should continue to grow in order to make a difference between successful and unsuccessful agents. This barrier can be overstepped by the activation of the wind feature included in the new simulator.

In real disaster situations, it might happen that the number of fire brigades is not sufficient for extinguishing a certain fire but may be high enough to control its spread. This is usually accomplished by preemptively watering non-burning buildings close to the fire border ("preemptive extinguishment"). In the new simulator, the amount of water used on a building will accumulate, then vaporize and thus cool the building. If the building is not yet burning this may even prevent it from catching fire. This new feature is visualized by the series of pictures in figure 4. As can be seen by the lower series, preemptive extinguishing of the diagonal row of buildings in the center prevents the ignition of all buildings behind.

In the RoboCupRescue domain fire brigades are allowed to use more than one nozzle during one *extinguish* command. By this it is possible to distribute water on more than one building at the same time (but note that the amount of water maximally allowed to be emitted during one cycle remains the same). Since extinguishing an ignited building requires virtually always more water than a single fire brigade can emit, this feature offered no tactical advantage so far. Together with the new feature of preemptively

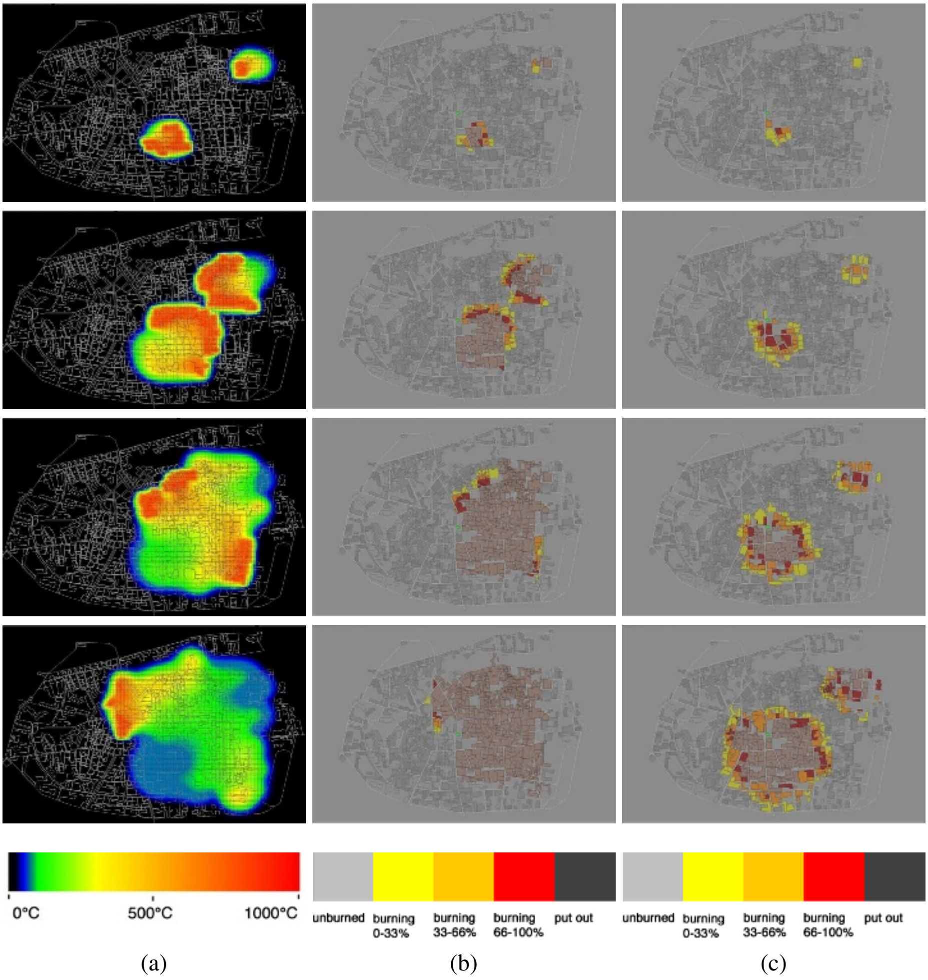


Fig. 3. From top to bottom: progress of fire spread of the new simulator, displayed in the internal model (a), in the RoboCupRescue world model (b) and compared to the progress of the old simulator (c)

extinguishing, however, it is possible for a single fire brigade to protect multiple buildings from ignition, since to protect a building requires less water than to extinguish it.

The simulator's runtime behavior has been evaluated on the three standard city maps used for the competition, which are *Kobe*, *Virtual City* and *Foligno*. On each map, we simulated, under the same settings, ten times a fire outbreak for a duration of 300 cycles. The simulations where carried out within a Java virtual machine (Blackdown Java HotSpot 1.4.1) on an AMD Athlon 700 MHz computer running a Linux operation system. Table 2 summarizes the average computing time for one cycle of the simulation on all of the three maps. Although this measurements do not include network communication

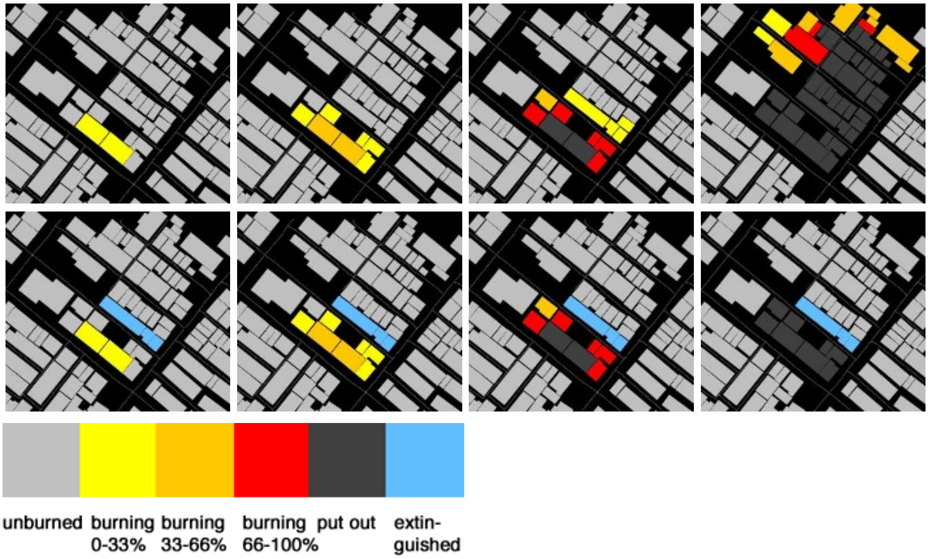


Fig. 4. From left to right: the new feature *preemptive extinguishing*. Upper row: fire spread without prevention. Lower row: fire spread prevention due to watering the diagonal building row in the center (blue) in advance

Table 2. Runtime measurements of the new simulator. The first row provides the employed city map, whereas the second row provides it's complexity, denoted by the number of buildings and air cells involved in the simulation. The other rows provide average, standard deviation, maximum and minimum of calculation time within one cycle of the simulation

Map	Complexity	Average	Standard Deviation	Max	Min
kobe	733 buildings, 5896 cells	10.6ms	7.8ms	73ms	6ms
virtual city	1269 buildings, 6972 cells	12.8ms	8.1ms	85ms	8ms
foligno	1085 buildings, 17214 cells	24ms	9.6ms	85ms	17ms

time, it can clearly be seen that the new simulator complies with the domain's time constraint of $500ms$.

5 Outlook

The introduced fire simulator makes a clear step towards close-to-reality simulation of urban disasters. However, due to the high complexity of urban fire spread, this step is just the beginning. With increasing computing power we will be able to contribute more detail to the domain: Firstly, the simulation of fire could be carried out within entities smaller than houses, such as floors and rooms. This feature would make it easier for fire fighters to decide which part of the building they should extinguish in order to avoid fire trespassing to other buildings. Secondly, the air grid model could be realized in three dimensions, leading to a more realistic simulation of fire propagation, especially in the case of higher buildings. Thirdly, the simulator could be extended by the simulation of smoke trails, which have a physical and psychological effect on civilians.

Particularly the first and third improvement are likewise fundamental to other simulators in the domain. The collapse and civilian simulator, for example, might implement more realistic responses of buildings and civilians to fire. The introduced fire simulator has been prepared for being extended towards those improvements.

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