Formal Analysis of Search-and-Rescue Scenarios

Project for Formal Methods for Concurrent and Realtime Systems course

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Abstract

This document presents a formal model implemented with Uppaal of search-and-rescue scenarios. Inside a rectangular map of arbitrary size, civilian *survivors* have to be brought to safety by either reaching an exit or being assisted by *first-responders*. *Drones* surveys the area and coordinate the rescue efforts by instructing *survivors* on what to do. The model then undergoes formal verification to highlight key behavioral aspects and identify optimal configurations for maximizing *survivor* safety.

Contents

1 High Level Model Description

The model adopted for the search-and-rescue mission involves 3 different types of agents: *survivors*, *first-responders* and *drones*. They are placed in different numbers inside a rectangular map, where exits (i.e. safe zones reached by survivors to get to safety) and fires are fixed in placed from the beginning of the scenario.

The key characteristics of the agents are these:

- **Survivors**: Can be in 3 different states, depending whether they find themselves near a fire or if they are following instructions
  - **In-need** (i.e. near a fire): They cannot move and needs to be assisted. After T_v time units, they became a casualty
  - **Busy**: The survivor is following an instructions and can be either assisting directly or contacting a *first-responder* to get help
  - **Moving**: When survivors are not near a fire or busy enacting some instruction, they can move towards an exit to get to safety following some *moving policy*
- **First-responders**:
  - **Assisting**: When a survivor *in-need* is within a 1-cell range, the *first-responder* will assist them for T_{fr} time units. After that, the assisted survivor is considered safe
  - **Moving**: When free from other tasks, the *first-responder* can move following some *moving policy*
- **Drones**: They survey their surroundings, limited by the field of view N_v of the sensors, and following a pre-determined path moving 1 cell at each time step. When two survivors, one *in_need* and one free, are detected the drone can instruct the free survivor to assist the *in_need* directly or to contact a *first-responder*

1.1 Model Assumptions

To simplify the model described in the assignment, the following assumptions have been made:

- The map is a 2D grid with a fixed number of rows and columns, and fires and exits are static (i.e. they won't change during simulation)
- Movements from one cell to another allows for diagonal movements. Therefore, the distance can be esily computed as the maximum between the difference of the x and y coordinates
- Movements of *survivors* and *first-responders* towards a human target (e.g. a *survivor* goes to a *first-responder*), are modeled with a wait state, where the agents remains idle for the duration of the movement, and then with a change in coordinates. This reduces the complexity of the model, lowering the number of states of the simulation and thus speeding up the verification process
- Drones know the global position of all the *first-responders* and their status, at any given time. This allows them to instruct *survivors* to contact the nearest *first-responder*
- All *survivors* know the location of the exits and can determine the nearest one
- *survivors* cannot start the simulation inside a fire cell

2 Model Description and Design Choices

2.1 State and Parameters Representation

Each agent type (*survivor*, *first-responder*, *drone*) is represented by an automaton, called **template** in Uppaal. These templates are characterized by many different parameters, and are implemented in Uppaal in the following way:

- The template signature (the parameters list) contains only one constant parameter, the agent id, annotated with a custom type defined as an integer with the range of possible ids (e.g. `typedef int[0, N_DRONES-1] drone_t;`). This way, by listing the template names in the *System declarations* (`system Drone, Survivor, FirstResponder;`), Uppaal can automatically generate the right number of instances of each template;
- The other agents' parameters (e.g. N_v, N_r, T_{zr}, etc.) are defined in constant global arrays (e.g. `const int N_v[drone_t] = {1, 1};`). Each template instance can then index these arrays with its own id as an index for these arrays (e.g. `N_v[id]`).

This setup allows to easily define the simulation parameters all inside the *Declarations* section, thus without modifying neither the templates nor the *System declarations*, and to easily assign different parameters to each template instance.

2.1.1 Map Representation

Desipite each agent holding internally its own position, a global representation of the map is needed for agents who require to know the state of other agents (e.g. drones need to know the position of *first-responders* to instruct *survivors* to contact them).

```
// Map cell status enumeration
const int CELL_EMPTY =      0;
const int CELL_FIRE =       1;
const int CELL_EXIT =       2;
const int CELL_FIRST_RESP = 3;
const int CELL_SURVIVOR =   4;
const int CELL_ZERO_RESP =  5;
const int CELL_IN_NEED =    6;
const int CELL_ASSISTED =   7;
const int CELL_ASSISTING =  8;

typedef int[0, 8] cell_t;

// Map array
cell_t map[N_COLS][N_ROWS];
```

The map is represented as a 2D grid of cells, with each cell indicating which type of human agent is within (drones positions are not neeed, so they are not included in this representation). This choice is made to avoid each agent holding a reference to all other agents, which would make the model more complex and harder to maintain.

When one agent changes position, it updates the map accordingly. For example, when a *survivor* moves, it empties the cell it was occupying and fills the new cell with its type.

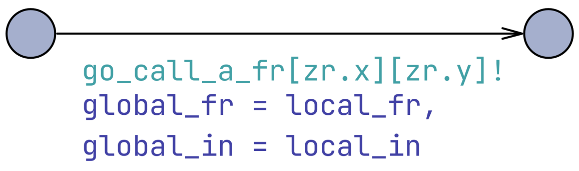
```
  void move(int i, int j) {
    set_map(pos, CELL_EMPTY);
    pos.x += i;
    pos.y += j;
    set_map(pos, CELL_SURVIVOR);
}
```

2.2 Syncronization and Message Passing

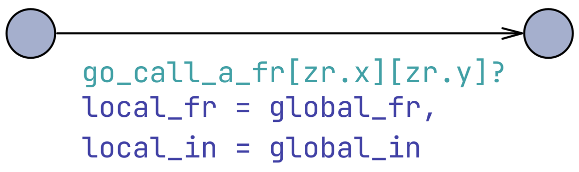
Between the different agents, there are some interactions that require a way to pass a payload. For example, when a *survivor* is instructed by a *drone* to contact a *first-responder*, the *survivor* must receive from the *drone* both the positions of the *first-responder* and that of the one *in-need* to assist.

This synchronization with message passing is implemented via Uppaal's built-in channels, augmented with global variables used to temporarily store the payload. The channels themselves are 2D matrices to allow targeting a specific agent. Each agent can trigger a channel at a given coordinate or listen at a channel on its own current position.

Following the previous example, the synchronization follows these steps:
1. The *drone* saves the positions of the target *first-responder* and *in-need* in two global variables and then triggers the channel at the coordinates of the targeted *survivor*.
2. The *survivor*, upon receiving the signal through the channel, reads the global variables to get the positions of the *first-responder* and *in-need*.



```
go_call_a_fr[zr.x][zr.y]!
global_fr = local_fr,
global_in = local_in
```



```
go_call_a_fr[zr.x][zr.y]?
local_fr = global_fr,
local_in = global_in
```

2.3 Moving Policies

Both *survivors* and *first-responders* are characterized by a custom moving policy. *Survivors* use this moving policy to reach the nearest exit, while *first-responders* use it to reach a *survivor* in need of assistance.

These moving policies all function in the same way, given a target position they produce the next move to take towards the target. Therefore they can be abstracted and implemented in a generalized way.

In order to support random choices, the moving policy implementation works as follows:
- On the edge where we want to perform the move, a non-deterministic selection of offets `i` and `j` is performed to identify a possible adjacent cell to move to (shown in Figure 1);
- The function `is_move_valid(i, j)` evaluates whether a given adjacent cell is a valid move or not, using the selected moving policy.

To experiment with different moving policies, we have impleted 2 simple policies:

- The **random** policy simply checks if the move is feasible (i.e. wheter the cell is not occupied by a fire or another agent). In Figure 2 we can see that the move is valid if the cell is empty. By “enablig” all the feasible moves, the model non-deterministically selects one of them;
- The **direct** policy enables only the moves with the lowest direct distance to the target. As shown by Figure 3, if more than one adjacent cell have the same distance to the target, the policy enables all of them and the model will randomly select among those.

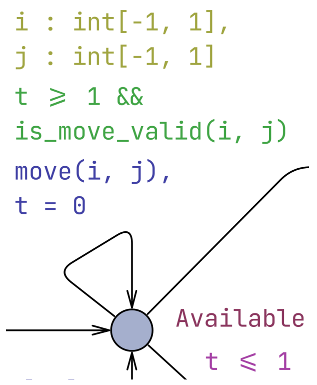


Figure 1: Moving edge

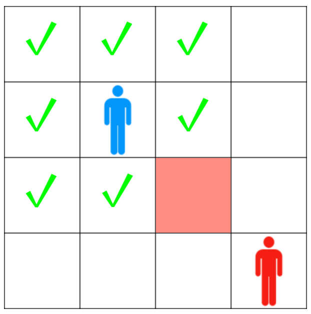


Figure 2:
Moving policy `RANDOM`

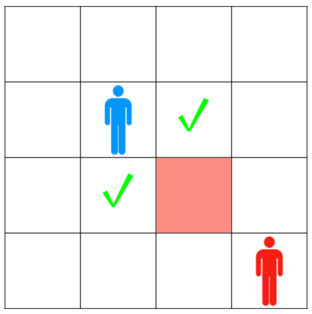


Figure 3:
Moving policy `DIRECT`

Below are the implementations of the two moving policies. The *direct* policy computes the distance of the best feasible move to the target, and then enables all those moves with that same distance. The policy is implemented this way in order to avoid preferring one direction over another if more than one move has the same distance to the target.

```
// Random policy allows all movements that are feasible
bool random_is_move_valid(pos_t pos, pos_t move, pos_t target, cell_t type) {
    return is_move_feasible(pos, move, type);
}

// Direct policy follows the best direct path (i.e. without considering
obstacles)
bool direct_is_move_valid(pos_t pos, pos_t move, pos_t target, cell_t type) {
    int min_distance;

    if (!is_move_feasible(pos, move, type))
        return false;

    // Find the distance to the target of the best possible move
    min_distance = compute_best_move_distance(pos, target, type);

    // A move to be valid must have minimum distance among the possible moves
    return distance(move, target) == min_distance;
}
```

2.4 Templates

2.4.1 Initializer

2.4.2 Surivor

At the beginning of the simulation, *survivors* position themselves in the map on pre-determined coordinates. If they are near a fire they become *in_need* otherwise they are considered *survivors*.

Survivors *in-need* cannot move and if not assisted within T_v time units they became a casualty, otherwise they are became safe. This behavior is modeled with bounds on the *survivor*'s clock: when T_v time is exceeded, the model must go to the `Dead` state. In both cases they leave the simulation freeing the map cell they were occupying.

Other *survivors* that are not near a fire, defaults to moving towards an exit following their *moving policy*. This movement can stop in 3 cases:

- If they move within a 1-cell range from an exit, they become safe and leave the simulation freeing the map cell they were occupying;
- If they receive an instruction from a *drone*, either to directly assist someone *in-need* or calling a *first-respoinder*, they stop targeting one of the exists and start following the instruction. In both cases, the survivor reaching the new target is modeled with a wait equal to the distance to the target, rather than an actual movement in the map. Although this does not properly models the simulated scenario, in particular the interaction between moving agents in the map, it is necessary in order to keep the model simple and verification times acceptable.7
- When they have no moves available. This could due to either the map topology being such that the survivor is blocked, or the *moving policy* not allowing any moves. For example, the `DIRECT` moving policies presented before, can possibly lead to a survivor being stuck in a loop where moving around an obstacle frees the previous cells that is the reselected. We assumed these cases acceptable because we deemed reasonable that the map topology could be challenging and that civilians could struggle finding the proper path.

2.4.3 First-responder

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2.4.4 Drone

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2.4.5 Initializer

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3 Properties

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4 Conclusion

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