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Knowledge-based Reactive Planning and Re-planning – A Case-Study Approach

1st Ramzi Djemai
Dept. of Computer Science & Applied Computing
London Metropolitan University
London, UK
r.djemai@londonmet.ac.uk

2nd Vassil Vassilev
Dept. of Computer Science & Applied Computing
London Metropolitan University
London, UK
v.vassilev@londonmet.ac.uk

3th Karim Ouazzane
Dept. of Computer Science & Applied Computing
London Metropolitan University
London, UK
k.ouazzane@londonmet.ac.uk

4rd Maitreyee Dey
Dept. of Computer Science & Applied Computing
London Metropolitan University
London, UK
m.dey@londonmet.ac.uk

***Abstract*—When a disaster strikes, man-made or natural, evacuation plans are put under immediate constraints, including topological, temporal, and spontaneously occurring events such as fire, smoke and obstacles introducing bottlenecks and impeding ingress and egress. Planning for uncertainties arising from indoor evacuations can be complex as there's a fine balance to strike between a too-detailed plan and one that's too vague. Such constraints apply to office and residential buildings, airports, mining sites, stadiums, ships, etc. Although some indoor spatial models have been developed, many are complex, and their applicability is non-universal. This paper proposes an innovative approach that harnesses the power of the Semantic Web Rule Language (SWRL) based on Web Ontology Language (OWL) to enhance existing evacuation planning methods through data-rich modelling. The OWL ontology serves as a formal representation of real-world concepts, their relationships, and properties. To demonstrate its application, the ontology is implemented in a case study involving London Metropolitan University's Tower Building, and its design is elucidated in this paper.**

***Index Terms*—Indoor Emergency Evacuation Management, Ontological Modelling, Planning Heuristics, Event-driven Re-planning**

I. Introduction

Ontology engineering is the process of building formal representations of a set of concepts within a given domain and the relationships between such concepts. Complexities in evacuation planning primarily stem from planning under uncertainty where the environment changes dynamically due to uncontrollable events compounded by widespread lack of indoor communication infrastructure and incomplete information(1).

Our proposed approach differs from the above traditional methods as it leverages the power of OWL ontology to represent everything about the problem domain whilst maintaining the semantic richness and real-world expressivity essential in spatial and conceptual knowledge representation. One of the most significant advantages of using an ontology-based approach is the support for automated reasoning, which includes inferring new knowledge based on the existing data and identifying inconsistencies within the ontology.

II. Background

A rule-based approach is one of the most straightforward approaches in evacuation path planning (2). This usually involves plans based on predefined procedures and/or rules which provide instructions to guide occupants to safety. However, such rule-based systems typically do not account for the dynamic nature of emergency evacuations. The second type of evacuation path planning uses simulation models to simulate the movement of occupants and predict evacuation scenarios and hazards (3). Typically, such an approach uses computational fluid dynamics or agent-based modelling to identify optimal evacuation paths. However, this approach is usually resource-heavy and may not react to changing conditions.

Similarly, Geographic Information Systems (GIS) and Linear and Network Optimisation Models do not provide personalised evacuation path planning and they, too, do not fully capture or react to real-world evacuation dynamics or changes in occupant states and actions (4). Other more powerful and more common approaches include machine learning Models (5), optimisation techniques (6), and heuristic approaches (7). Machine Learning (ML) models can be powerful in optimising evacuation plans and predicting and analysing a series of complex evacuation scenarios. However, these tend to require extensive data for training, and their ability to adapt in real time to unforeseen events is limited unless they are continuously updated with new data. Optimisation models, including network flow or linear programming, represent the space mathematically, often focusing on maximising or minimising specific evacuation objectives such as finding the shortest path. (8) This approach is much less flexible and is entirely model-dependent – they neither offer a semantic understanding nor problem-domain reasoning beyond their pre-defined

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mathematical model. Heuristic approaches, including but not limited to ant colony optimisation (9) and genetic (10) and agent-based models(6), tend to be more suited to this research problem domain and far more flexible. For example, such an approach typically uses grids, graphs or a hybrid form of space representation (other data structures) to represent the search space depending on the specific algorithm. Heuristic algorithms leverage these representations to explore possible solutions (find a path) efficiently. However, the aforementioned data structures provide a more abstract and simplified representation of the search space, focusing more on spatial and geometric aspects of the problem, which ignores rich, real-world concepts and their relationships.

The prevalent similarity across traditional approaches to evacuation planning is their reliance on abstract representations that often neglect the context-rich details of real-world environments. Common graph-based models use nodes and edges and are often implemented using adjacency matrices. However, these models usually offer a limited perspective, focusing primarily on the spatial configuration without capturing the intricate semantics of physical elements like doors, rooms, obstacles, and corridors or logical elements such as distance, actions, events, and situations (11).

The proposed approach in this paper extends beyond conventional methods by incorporating ontological engineering within the domain of evacuation planning to address inherent challenges present in non-deterministic (dynamic) planning scenarios. Implementing an ontology-based approach enables the capture of semantic richness and real-world expressivity necessary for modelling intricate evacuation situations. In this context, OWL was leveraged to develop a knowledge-based representation for indoor evacuation planning and re-planning, as illustrated through a case study.

III. Knowledge-Based Approach

To comprehensively knowledge-represent the problem domain, we tailor our approach by partitioning our ontology to reflect two fundamental dimensions of indoor evacuation planning:

A. Physical Domain

At the foundational level sits our building ontology, which encapsulates the physical aspects of a building—rooms, corridors, staircases, and other structural elements. This representation forms the backbone of the topological model, enabling precise mapping of the physical concepts and spaces where evacuation procedures occur.

B. Logical Domain

To bridge the gap between static infrastructure and planning dynamics, we incorporate a logical layer that contextualises paths, situations, events, and actions. This aspect of the ontology represents the abstract relationships and potential sequences of evacuation events, facilitating intelligent and responsive evacuation planning. Logical concepts include but are not limited to paths, situations, events and actions. The representation of the evacuation dynamics forms the second layer of our ontology. This dimension is essential for depicting the behavioural aspects of evacuation and encompasses the following micro-models:

- **Situations**: This micro-model consists of all possible situations (states) an individual occupant can be in during an evacuation. Situations are distinct, such as $'person\_in\_corridor'$ or $'person\_in\_office'$. Each situation is interlinked with the next using actions, forming a sequential chain that dictates the flow of movement through the space. Eg., *[occupant in room]* **(s1)**, take action *[exit current room]* **(a1)**, *[occupant in corridor]* **(s2)**. Each situation is defined with metadata that includes a unique identifier for the occupant(s) involved and the physical location associated with the state. For example, the situation $'person\_in\_corridor'$ has parameters such as the person's identifier and the specific corridor they are located in. This detailed parameterisation allows for precise tracking of occupants' states during an evacuation.
- **Events**: To model real-world emergency events that can impact evacuation paths, such as fire alarms, bottlenecks, collapsed ceilings, etc., this ontological micro-model represents evacuation events that may be triggered at random during an emergency evacuation, providing the situational awareness necessary for the planner to react accordingly. Events are defined by their type and impact, with parameters that tie them to the specific situations they affect. For instance, an event such as $'fire\_alarm\_triggered'$ has parameters specifying the location of the alarm and any occupants affected. This ensures that when an event alters a situation, it does so with reference to the correct parameters, leading to a logically consistent sequence of situations.
- **Actions**: The Actions micro-model is used to conceptualise movement through a building (navigation), which consists of prescriptive, policy-based rules written in SWRL, descriptive (asserted axioms describing the world) and prescriptive rules, which are used to direct occupants toward safe exits and ensure compliance with evacuation and building policies. Each action within the ontology is defined with parameters that ensure continuity. For example, the action $'walk\_down\_to\_ebarriers\_on\_the\_left'$ has parameters for the occupant executing the action and their current location. This ensures that when an action results in a new situation, the parameters from the previous situation are carried forward accurately.

IV. Domain Knowledge Representation: Tower Building Case-Study

To illustrate the applicability of our ontology-based approach to evacuation planning, we selected London Metropolitan University's Tower Building (TB) as a case study. However, while the Tower Building serves as a practical example in this paper, the methodologies and ontology we present are designed to be universally applicable to any 3D structure with similar topological properties. As such, models derived from this case study are intended to be adaptable to a wide range of buildings. TB includes 11 accessible floors, each with a unique layout and a varying number of rooms, with some having their own inner rooms (rooms within rooms). Each floor can be accessed through two different staircases located on two sides of the building. Its first floor, known as the 'Piazza Floor', connects TB to other buildings through 'link bridges'. The details of the topological model design of the TB are described in the subsections below.

A. Topological Model

The topological model consists of all the concepts that together constitute a building. Fig. 1 outlined a model that describes the building and its different meta-levels from Events, Situations and Actions. As illustrated in the accompanying diagram below, the topological model is a complete ontological representation that encapsulates the physical structure and layout of a building in a hierarchical classification.

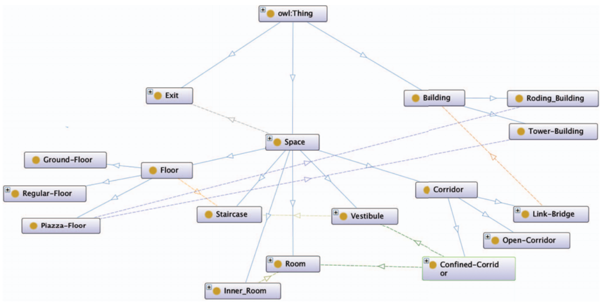

Fig. 1. An example of a topological model for Tower Building.

In Fig. 1, the super-class $'Building'$ includes three different types of buildings, though, for the purposes of this paper, only the Tower Building is used. Central to this model is the $'Space'$ super-class, which includes specific spaces as sub-classes such as $'Floor'$, of which there are three types, $'Ground-Floor'$, $'Regular-Floor'$, and $'Piazza-Floor'$. Each represents unique characteristics of the building's layout, modelling horizontal navigation through the space. Integral to the navigational aspect of the ontology are classes such as "Corridor", which includes three key sub-classes $'Open-Corridor'$, $'Confined-Corridor'$, and $'Link-Bridge'$, representing different types of passageways the planner can navigate occupants via. The $'Staircase'$ class is essential for vertical navigation crisscrossing floors, while the $'Exit'$ class represents egress points critical in evacuation scenarios. Vestibule areas in the Tower Building serve as junction points between floors and staircases.

B. Situations

The situations micro-model represents each state a person can be in during the evacuation process. Fig. 2 below shows a small selection of evacuation situations.

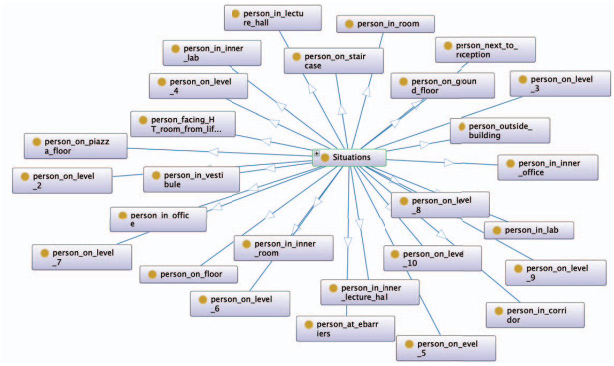

Fig. 2. Examples of individual situations for Tower Building/case-study scenarios.

Each situation is expressed in terms of its metadata and parameters that define three critical aspects: the logical description of the situation (e.g., $'person\_in\_room'$), the identity of the occupant(s) involved (e.g., John Smith), and the physical location associated with the state (e.g., Office T9a). This detailed parameterisation allows us to precisely track each occupant's state(s) during an evacuation, as shown in Fig. 3.

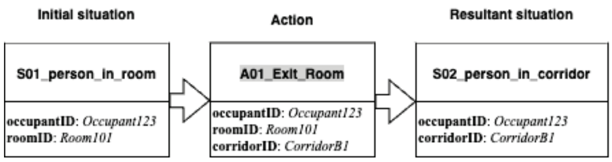

Fig. 3. Examples of individual situations for Tower Building/case-study scenarios.

C. Events

Events are asynchronous and binary – they're either on or off. Events affect situations, which in turn affects actions. Events are defined by their type and impact, with parameters that tie them to the specific situations they affect. For instance, an event such as $'fire\_alarm\_triggered'$ would include parameters specifying the location of the alarm and any occupants affected. This ensures that when an event alters a situation, it references the correct parameters, leading to a logically consistent sequence of situations.

As an example, in Fig. 4, the event $'Obstacle-Blocking'$ some object (door, chair, desk, wheelchair, etc.) prompts the re-planner to find an alternative route to bypass the obstacle. When such an event is triggered, an appropriate action is prescribed, and the situation changes accordingly depending on the type of situation in question. Table I below shows a simplified decision matrix outlining events and their impact on the re-planner by indicating a score ranging from 1-3. Events scoring below 3 allow the current evacuation plan to proceed

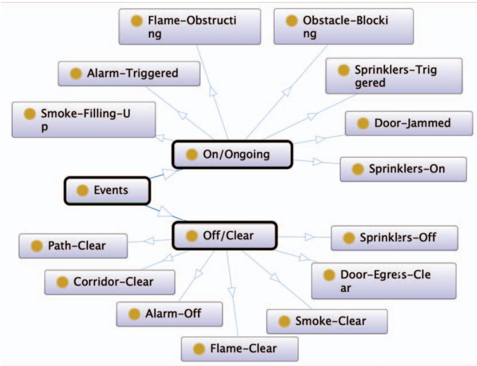

Fig. 4. Taxonomy of Events for case-study scenarios.

TABLE I
DECISION MATRIX FOR EVENT-TRIGGERED RE-PLANNING.

Event Name	Impact(1-3)	Triggers Re-planning(1-3)	Total
Flame-Obstructing	3 (High)	3 (Yes)	6
Alarm-Triggered	1 (Low)	1 (No)	2
Smoke-Filling-Up	3 (High)	3 (Yes)	6
Obstacle-Blocking	2 (Medium)	3 (Yes)	5
Sprinklers-Triggered	1 (Low)	1 (No)	2
Door-Jammed	3 (High)	3 (Yes)	6
Sprinklers-On	1 (Low)	1 (No)	2

unchanged. In contrast, events scoring 3 activate the re-planner to modify the evacuation plan accordingly.

D. Actions

Actions are object properties which are classified into three distinct categories:

- Prescriptive: Actions or navigational commands such as `enter_corridor`, `exit_inner_room`, `turn_left`, `exit_out`, `exit_right`, etc.
- Descriptive: Asserted axioms which describe the space such as `Corridor` (**links-up**) `Room` and `Inner-Room` (**extends**), `Room`.
- Policy: SWRL rules that govern the evacuation planning from start to finish, which are in the form of triplets, connecting each situation to the next with an action. For example, the rule: `person_facing_HT_room_from_lift _vestibule(?x) walk_down_to_ebarriers _on_the_left(?x, ?y) -> person_at_ebarriers(?x)` contains an initial situation, $'person\_facingHT\_room\_from\_lift\_vestibule'$, a prescribed action $'walkdownstairs'$, which results in a new situation, $'person\_at\_e-barriers'$. Each action within the ontology is defined with parameters that ensure continuity. For example, the action $'walk\_down\_to\_ebarriers\_on\_the\_left'$ has parameters for the occupant executing the action and their current location. This ensures that when an action results in a new situation, the parameters from the previous situation are carried forward accurately.

V. KNOWLEDGE-BASED PLANNING: STATIC PATH PLANNING

For offline planning that does not require any re-planning, a representation of the physical domain, as discussed in Section III-A, would be necessary. In such scenarios, a simple A* algorithm would likely suffice. Our approach employs Lifelong Planning A* (LPA*), an incremental heuristic search algorithm which calculates a one-off plan, taking into account events that do not impact the established evacuation route or when no events are triggered at all. The planner uses a heuristic function to estimate the distance to the goal, which is the nearest safe exit and pre-calculates the shortest path for an occupant based on their initial location, considering the building's physical layout. The topological model, the ontological representation of the building's physical layout, provides the static data that LPA* requires to function. This includes the location of rooms, corridors, exits, and other structural elements. In our planning procedure, some events are defined as 'non-impact events' which do not necessitate a deviation from the pre-computed path. These include minor incidents or alarms that do not block or threaten the planned routes. LPA*'s incremental nature allows us to disregard such events, thus avoiding unnecessary re-calculations.

Fig. 5 illustrates an evacuation scenario where an event occurs without affecting the existing evacuation plan.

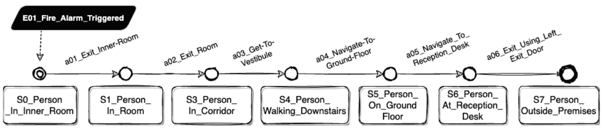

Fig. 5. Ontology-based planning scenarios for Tower Building over multiple floors.

VI. EVENT-DRIVEN RE-PLANNING: DYNAMIC PATH PLANNING

Since our approach accounts for the non-deterministic nature of planning under dynamically occurring events, a simple offline map for planning purposes alone is insufficient. Similar works, such as (12), (13) and (14), have instead used the Manhattan approach, suggesting it may be more suitable due to the unforeseen dynamics of the evacuation where events may happen and rerouting is involved, which will trigger the re-planner. However, LPA* uses the partitioning of our ontology, specifically the logical domain representation outlined in Section III-B, which acts as a decision support system for the re-planner, allowing it to execute polymorphic responses to events. For example, if an event such as a fire outbreak is triggered, altering a previously safe plan, the re-planner can use the logical domain representation, specifically, the actions micro-model, to instantiate alternative actions. It maps the current situation to potential subsequent situations through SWRL rules as tabulated in Table II, which generates a new sequence of actions—each a triplet of [situation-action-situation] that guides occupants along a revised path to the goal state.

TABLE II
EVACUATION PLANNING POLICIES FORMULATED USING SWRL FORMATTED AS TRIPLETS.

Current Situation	Action	Resultant Situation
person_in_inner_room(?x)	exit_inner_room(?x, ?y)	person_in_room(?x)
person_in_inner_room(?x)	exit_inner_room(?x, ?y)	person_in_room(?x)
person_on_level_3(?x)	head_downstairs_to_floor_2(?x, ?y)	person_on_level_2(?x)
person_in_lab(?x)	exit_room(?x, ?y)	person_in_corridor(?x)
person_in_lecture_hall(?x)	exit_room(?x, ?y)	person_in_corridor(?x)
person_in_room(?x)	exit_room(?x, ?y)	person_in_corridor(?x)
person_in_corridor(?x)	exit_to_vestibule(?x, ?y)	person_in_vestibule(?x)
person_in_vestibule(?x)	exit_to_staircase_left(?x, ?y)	person_on_staircase(?x)
person_at_ebarriers(?x)	exit_through_ebarriers(?x, ?y)	person_next_to_reception(?x)
person_in_inner_lecture_hall(?x)	exit_inner_room(?x, ?y)	person_in_lecture_hall(?x)
person_next_to_reception(?x)	walk_out_of_building(?x, ?y)	person_outside_building(?x)
person_in_inner_lab(?x)	exit_inner_room(?x, ?y)	person_in_lab(?x)
person_in_office(?x)	exit_room(?x, ?y)	person_in_corridor(?x)
person_on_level_2(?x)	head_downstairs_to_piazza_floor(?x, ?y)	person_on_piazza_floor(?x)
person_on_piazza_floor(?x)	head_downstairs_to_ground_floor(?x, ?y)	person_on_ground_floor(?x)

The re-planner constantly checks for branch-offs (alternative routes) along the existing path throughout the planning procedure. The following evacuation diagram shown in Fig. 6 illustrates a series of different evacuation scenarios, three of which are distinct:

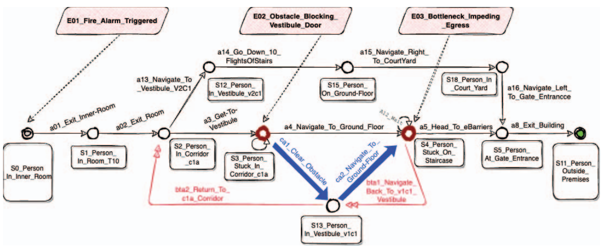

Fig. 6. Ontology-based planning scenarios for Tower Building over multiple floors.

Scenario 1 – Event triggered, no obstacles encountered, no re-routing or backtracking involved

`Path = S0, A01, S1, A02, S2, A13, S12, A14, S15, A15, S18, A16, S5, A8, S11`

All evacuation scenarios start with an initial trigger event, which is always a fire alarm for this case study. This evacuation plan is a direct, unimpeded path to safety. This is the ideal evacuation scenario, where the path from the starting point to the final exit is straightforward, with no interruptions or deviations.

Scenario 2 – Events triggered, obstacles encountered, re-rerouting involved but not backtracking

`Path = S0, A01, S1, A02, S2, A3, S3, CA1*, S13, CA2*, S4, A5, S5, A8, S11`

This scenario involves an event (E02) that requires the re-planner to find an alternative, yet still direct, route to the exit (S11) by suggesting Corrective Actions (CA1 and CA2), highlighted in blue.

Scenario 3 – Events triggered, obstacles encountered, re-routing and backtracking involved

`Path = S0, A01, S1, A02, S2, A3, S3, CA1, S13, CA2, S4, A12, S4, BTA1, S13, BTA2, S2, A13, S12, A14, S15, A15, S18, A16, S5, A8, S11`

This scenario is more complex, involving multiple events, re-routing (in blue) and backtracking (in red). It illustrates the dynamic nature of real-life emergencies, where evacuation conditions can change rapidly as a result of spontaneous events and require a flexible, reactive approach. After encountering an obstruction (E02) and taking a rerouted path through Corrective Actions (CA1 and CA2), further events occur, requiring two Backtracking Actions (BTA1 and BTA2) due to persistent hazards. This scenario tests the robustness of the evacuation procedure by incorporating not just alternative routes but also the necessity to revisit and reassess previous decisions, backtracking to prior locations (S13, S2) before finding a clear path to exit the building (S11)

VII. CONCLUSION AND FUTURE WORK

This paper primarily focused on introducing a novel ontology-based approach to planning and re-planning for indoor evacuation scenarios. Utilising the Web Ontology Language (OWL), we have presented a knowledge-based methodology used to represent the indoor evacuation planning domain comprehensively. The two-layered ontology provides a robust framework for capturing the static and dynamic nature of emergency evacuations. It offers a more nuanced and adaptable methodology compared to traditional models, which often overlook the complex, real-world dynamics of emergency scenarios. Our approach significantly enhances the heuristic planning and event-driven re-planning algorithms by providing a rich, semantic model of evacuation scenarios' physical and logical aspects. This work serves as a foundational step towards our ongoing development of a comprehensive knowledge-based planning framework.

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