Building exploration with leeches Hirudo verbana

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Abstract

Safe evacuation of people from building and outdoor environments, and search and rescue operations, always will remain actual in course of all socio-technological developments. Modern facilities offer a range of automated systems to guide residents towards emergency exists. The systems are assumed to be infallible. But what if they fail? How occupants not familiar with a building layout will be looking for exits in case of very limited visibility where tactile sensing is the only way to assess the environment? Analogous models of human behaviour, and socio-dynamics in general, are provided to be fruitful ways to explore alternative, or would-be scenarios. Crowd, or a single person, dynamics could be imitated using particle systems, reaction-diffusion chemical medium, electro-magnetic fields, or social insects. Each type of analogous model offer unique insights on behavioural patterns of natural systems in constrained geometries. In this particular paper we have chosen leeches to analyse patterns of exploration. Reasons are two-fold. First, when deprived from other stimuli leeches change their behavioural modes in an automated regime in response to mechanical stimulation. Therefore leeches can give us invaluable information on how human beings might behave under stress and limited visibility. Second, leeches are ideal blueprints of future soft-bodied rescue robots. Leeches have modular nervous circuitry with a rich behavioral spectrum. Leeches are multi-functional, fault-tolerant with autonomous intersegment coordination and adaptive decision-making. We aim to answer the question: how efficiently a real building can be explored and whether there any dependencies on the pathways of exploration and geometrical complexity of the building. In our case studies we use templates made on the floor plan of real building.

Keywords: Leeches, evacuation, bionics, bio-inspired algorithms, living technologies

1 Introduction

During the last decades there is a growing interest of scientists on the safety of people when gathering in indoor and outdoor environments like big buildings, sporting arenas, music halls, shopping centers, etc. The main issue in all these cases concerns the evacuation process in case of emergency and, more specifically, how it will be feasible to prevent accidents during it. It has been indicated that crowd safety and comfort not only depend on the design and the operation of the under study environment itself, but also relies on the behaviour of each crowd individual [30]. From historical point of view, the early approach of motion prediction applied to large crowds of pedestrians was mainly based on the modelling of the crowd as a continuous homogeneous mass that behaves like a fluid flowing along corridors [32]. Albeit, quest for more realistic and efficient in case of emergency, modern evacuation modelling approaches that will be able to reproduce phenomena like herding behaviour, clogging, arching near the exits, individualism, grouping and other behaviours, which are related with the process is still an on-going process. In the meantime, there are several works in literature [22] dealing with these issues while indicating different approaches that try to envisage major features of human behaviour, such as the decentralized crowd behavioral model [48], particle dynamics for grouping [8], social forces [31], data driven models [40, 39, 5], etc. Moreover, in some of these models, pedestrians are ideally considered as homogeneous individuals, whereas in others, they are treated as heterogeneous groups with different features (e.g., gender, age, psychology). In general, crowd movement models can be categorized into top-down or macroscopic and bottom-up or microscopic ones [55]. Macroscopic models like lattice-gas [41] and fluid-dynamic [31] focus on the total number of the members of the crowd ignoring possible differences on the individual behaviour. Microscopic models study the spatial and temporal behavior of each of the individuals and their interaction with the other members of the crowd. These are methods, where collective phenomena emerge from the complex interactions among individuals (self-organizing effects), thus describing pedestrian dynamics in a microscopic scale. Cellular Automata (CA) [57] models, agent-based model and social-force models belong to this category [56, 51, 61, 45, 26, 11].

Analogous models of human behaviour, and socio-dynamics in general, are provided to be fruitful ways to explore alternative, or would-be scenarios. Crowd, or a single person, dynamics could be imitated using particle systems [13, 29], reaction-diffusion chemical medium [1], heat-transfer [42], electro-magnetic fields [52]. Nevertheless, most of the proposed models either agent-based or not try to mimic as close as possible human behaviour during evacuation and are considered to fulfill their promises based to the corresponding quantitative and qualitative results. The latest are considered a well known first approach on the effectiveness and the robustness of the models to reproduce the aforementioned phenomena synonymous to the prominent human crowd behavior during evacuation and in emergency situations. Towards this direction, scientists have used other species and living organisms as a fine substitute to both humans and corresponding models found in literature while trying to simulate evacuation in different environments. For example, Shiwakoti et al. [50] in analogy to Burd et al., Couzin and Frank and Chowdhury et al. works on traffic modeling with different species of ants [10, 15, 14] have used Argentine ants as a proxy for humans and studied their behaviour under panic to test different structural features to the panic escape in a chamber with fixed dimensions [49]. In a similar manner, we have used slime mould to bio-mimic the human evacuation from a building and, furthermore, to develop a corresponding computational *Physarum*-inspired crowd evacuation model based on CA by taking into account while mimicking the *Physarum* foraging process, the food diffusion, the organism's growth, the creation of tubes for each organism, the selection of optimum tube for each human in correspondence to the crowd evacuation under study and finally, the movement of all humans at each time step towards near exit [35].

So it is clear that nowadays it is become more and more efficient to use living creatures as a real-world analog models and in a more generalized way of spatially-extended computing and technological systems. Most famous instances of analog modelling with living substrates include laboratory experiments with real ants on improved collective performance in distributed tasks, decision making and robotics [38, 20]; design and implementation of logical gates with soldier crabs [28]; development and manufacturing of sensors and computing circuits with slime mould *Physarum polycephalum* [2].

In present paper we employ leeches to study explorations of building in scenarios with limited visibility and sensing. A leech *Hirudo medicinal* and its South European analog *Hirudo verbana* are amongst most common living creatures explored in laboratory conditions. Leeches are ideal inspirations for amphibious soft or flexible search-and-rescue robots capable for reaching spaces not accessible by other devices amphibious [18, 16, 59, 17, 58, 60]. The reasons are following.

The leeches' neural networks are simple yet efficient, they are equivalent in their computational power to basic perceptrons [43]. Notably, a nervous system of leech became a test bed for modelling locomotion control [33, 43, 12, 25, 19, 36, 23, 6, 44], modulating behaviour of neuro-mediators [62, 4, 27], developmental processes in complex neuronal circuits [37], and mathematical and computers models of circuits responsible for regular pattern generations [54, 63, 47, 9].

A leech has exactly thirty two segments. A single segment of the leech's body contains isolated ganglion. It is capable for exhibiting swimming activity even when the segment has been neurally isolated from the rest of the leech's body [33].

A spectrum of leeches' behaviour traits is extensively classified [21]. The following pattern is reported by Dickinson and Lent [21]. A leech positions itself at the water surface in resting state. The leech swims towards the source of a mechanical or optical stimulation. The leech stops swimming when comes into contact with any geometrical surface. Then, the leech explores the surface by crawling. When a leech finds a warm (37-40°C) region the leech bites. There is also useful feature of context-modulate behaviour: a leech can respond to constant sensorial inputs with variable motor outputs [7].

Finally, behaviour of leeches in uniform spaces is well analyse. There leeches wander around uniformly and no preferential direction or location have been observed [24]. Results on leeches bevavior in complex geometries are scarce or non-existent. It is know that leeches show positive stigmotaxis and therefore crawl under logs for hiding or body cavities feeding. Till our recent paper [3] no result were on how geometrical constraints of a space shape leech's behavioural patterns. In [3] we found that a leech switches into exploration mode when it encounters a mechanical obstacle and a probability of returning from exploratory mode to crawling mode decreases proportionally to a distance from last mechanical obstacle. Therefore, when placed in a corridor with a raw of rooms on one side the leech explores rooms near end of the corridor with higher probability and rooms near the centre of the corridor with lower probability. Based on the results of our laboratory experiments we formalised behaviour of a leech in terms of probabilistic finite state machines with binary inputs. In the present paper we decided to go further and to study how leeches explore geometrical constrained areas with templates matching part of real buildings. The rationals for this study are as follows. What if a person tries to move towards an exit in total darkness and silence and absence of smell, by relying just on their tactile stimuli and having no previous knowledge of the building layout. How does pattern of exploration develop? Will the person explore the whole building? Or will stack in some particular parts? It should be further defined that the usage of such a scenario, i.e. where the human has limited senses and/or information received by the under study environment enables the possibility of bio-mimicking the human behaviour by a less complex biological entity with diminished behavioral abilities compared to humans like leeches. In such a way, the provided study and the corresponding results of the leeches under panic (the term "panic") should be also defined in a different base compared to the one arisen by the sociological science and referring to not rational behavioral due to emotional stress) sound promising without studying the physical and behavioral similarities and dissimilarities among leeches and humans in one-to-one basis.

2 Methods

We used three weeks old leeches *Hirudo verbana* obtained from Biopharm Leeches (Hendy, Carmarthenshire SA4 0X, UK). Leeches varied in size from 10 to 20 mm length in elongated state and 1-2 mm width. Leeches awaiting experiments were kept in securely covered, yet with air access, glass containers in a dechlorinated water away from direct sunlight. As per recommendation [53] leeches were kept in a cool, c. 15°C, environment to lessen their needs for feeding and to enhance their performance in exploration of experimental templates. The water was refreshed every other day. When moving leeches between storage containers and experimental templates we used non-serrated forceps.

In experiments we used template of the first floor of building B of the Electrical and Computer Engineering Department (ECE) of the Democritus University of Thrace (DUTh). The floor plan of the space is accurate and consistent with the real dimensions of the university building. This particular office layout was chosen because a range of experiments undertaken and computer models developed for this particular layout of rooms [34, 35]. By using the same template we make experiments with leeches compatible with our previous results and data obtained. The scenario adopted here considers a human

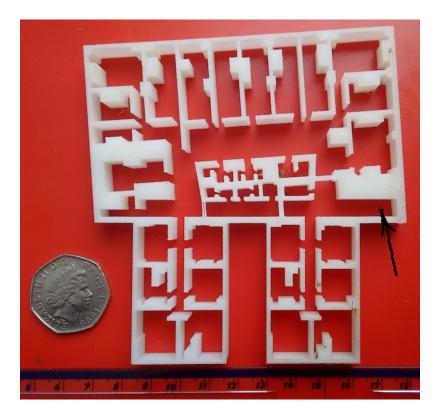


Figure 1: Photo of geometrical template used. Initial position of leech is shown by arrow.

randomly located in the aforementioned space. Please consider that no previous knowledge of the under exploration environment is provided to her/him while there is no light and sound and hence the human is not able to see or hear anything. By assuming that she/he is not able to use any of her/his senses, e.g. sense of touch, and is equipped only with a torch. The same constrains correspond in analogy to the leeches that will be used for the exploration of the template.

The template was printed from polylactic acid thermoelastic polyester (Fig. 1) with the maximum dimensions 11 cm by 10 cm and wall height 1 cm. The layout contains 24 rooms, each room has opening to corridors. Experimental template was cleaned to remove any substances with odour or state that might affect behaviour of leeches. The template was filled with dechlorinated water, depth 9 mm; the leeches were able to swim if they wanted too. The water was renewed to prevent metabolites and ions released by leeches to affect behaviour of their successors. The template was illuminated by LED lamp and the illumination level at the bottom of the template was 37 LUX. No sharp gradients of optical, chemical or electrical stimuli were allowed; the only stimulation occurred was mechanical one when leeches come into contact with walls of the template. Experiments

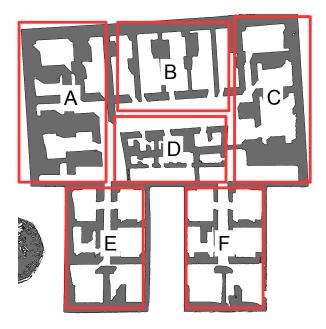


Figure 2: Separation of template into several domains.

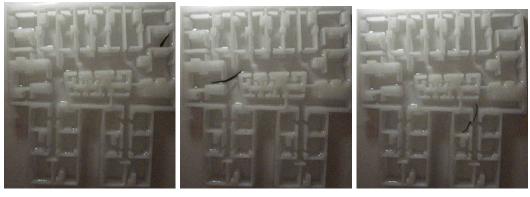
were conducted in a room temperature of 20°C. We conducted 20 experiments using 20 leeches; each leech was used once.

The experiments were recorded on Coolpix P90 digital camera, 640×480 pixels frame size and 25 frames per second speed. Each video was recorded for c. 30 min or till leech escapes, whatever happens early. The videos were analysed by in-house software written in Processing, as follows. For every second of video we extracted coordinates of pixels with colour values less than 30-50 in RGB mode (exact threshold was adjusted for each video). Such pixel represented body of the leach. Their coordinates with time tags were stored for further analyses. Configurations of leeches exploring the template were converted to overlay images with colours as follows. For any trial/video a duration of recording is normalised to the interval [0,1] and then mapped to a colour scale $(00B) \rightarrow (0BG) \rightarrow (RG0) \rightarrow (R00)$, i.e. the blue pixel represent leech at the beginning of experiment and red pixel at the end of experiment.

We separate the layout into six domains (Fig. 2) which will be referred to in further analysis and discussions.

3 Results

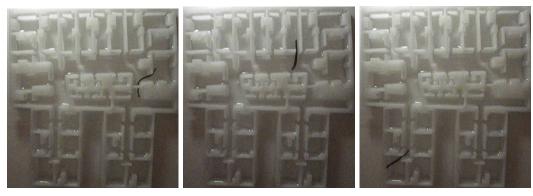
Snapshots of an experiment are shown in Fig. 3. The leech was placed by random selection in the right end of corridor of domain C, as indicated by arrow in Fig. 1. In first minute,



(a) 1 min

(b) 1 min 48 sec

(c) 2 min 39 sec



(d) 5 min 14 sec

(e) 13 min 30 sec

(f) 23 min 26 sec

Figure 3: Snapshots of a leech exploring template.

leech propagated to room right cornet room in domain C (Fig. 3(a)). It then explores the domain C and leaves for domain D, which is passed almost without exploration (Fig. 3(b)). In roughly two and half minutes the leech enters corridor in domain F and immediately proceeds to the first room near the entrance of the domain (Fig. 3(c)). After exploring rooms in domain F the leech returned to domain C (Fig. 3(d)) and then swim to domain B (Fig. 3(e)). Domain E is getting explored after twenty minutes of the experiment (Fig. 3(f)).

Time to color coded overlays of leeches in representative experiments are shown in Fig. 4. In experiments shown in Figs. 4(a) and (b), leeches explore mainly domain E, and they spent most of their time in domains A to D in experiment Fig. 4(c). A leech visits almost all domains by E in experiment Fig. 4(d). A sequence of domains visited, as seen in color coding is C, F, D, B, A, D, F. In this particular the leech escaped outside template from the domain F. Other illustrations show leeches predominantly visiting F (Figs. 4(e) and (f)), E (Fig. 4(g)) and both E and F (Figs. 4(h) and (i)).

We approximate a frequency of a leech to be in site x of a template as a number of experiments leech visited site x normalized by a total number of sites visited by leeches in all experiments. The frequency of visits might also reflect time a leech spends in the domain, in cases when leech does not remain still. The frequency of visits field of the experimental template is shown in Fig. 5. Frequency cut off for various levels of thresholds are presented in Fig. 6. From the frequency matrix (Fig. 5) we can calculate frequencies of leeches visiting domains: f(A) = 0.09, f(B) = 0.11, f(C) = 0.17, f(D) = 0.11, f(E) = 0.23, f(F) = 0.30. Thus we have the following hierarchy of leeches' preferences in visiting particular domains:

$$f(F) > f(E) > f(C) > f(A) > \{f(B), f(D)\}.$$
(1)

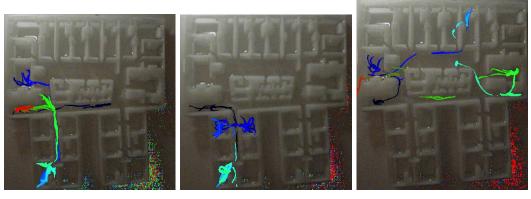
We see that leeches prefer to visit domain F and visiting more sites inside the domain F than in other domains of the template. Domain E is second most visited part of the template. Further preferences to go domain C. Domains A, B and D are less visited part of the template, or less explored domains.

Is the hierarchy (1) determined by complexity of the template? We calculate complexity of a domain as a number of corners in the domain normalised by total number of corners in the template. The idea is consistent with the findings of the many works reported in literature regarding the role of corners in indoor environments during evacuation under emergency. Thus, we get the following list of complexities: c(A) = 0.15, c(B) = 0.14, c(C) = 0.10, c(D) = 0.16, c(E) = 0.22, c(F) = 0.22. So in terms of complexity we have the following hierarchy:

$$\{c(E), c(F)\} > c(D) > \{c(A), c(B)\} > c(C).$$
(2)

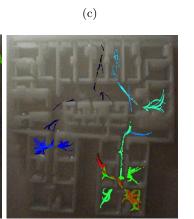
As we can see in the frequency of visits versus complexity of domains plot Fig. 7, there three clusters of domains:

1. moderate complexity and low frequency of visits: domains A, B, D



(a)

(b)





(e)

(f)

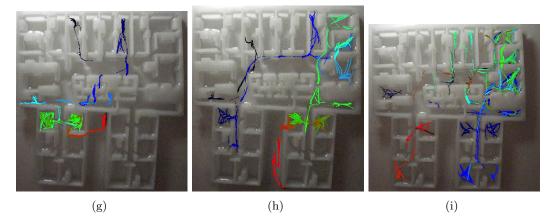


Figure 4: Time snapshots of selected experiments.



Figure 5: Frequency matrix normalized to gray level: 0 is white and 1 is black.

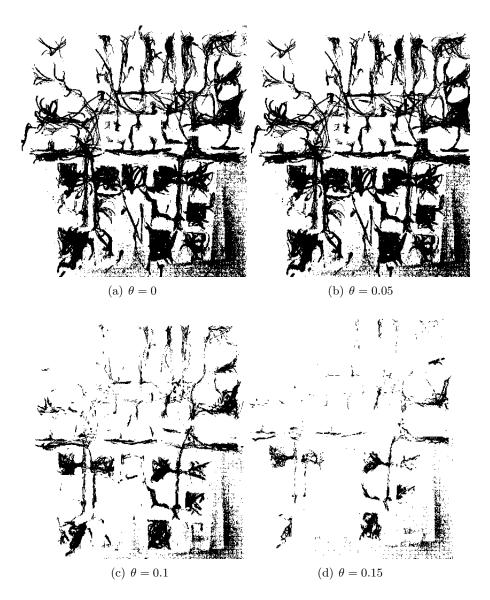


Figure 6: Threshold frequency matrix normalized to gray level. Only non-zero entries exceed threshold θ are shown by black pixels. Values of θ are shown in the captions to sub-figures.

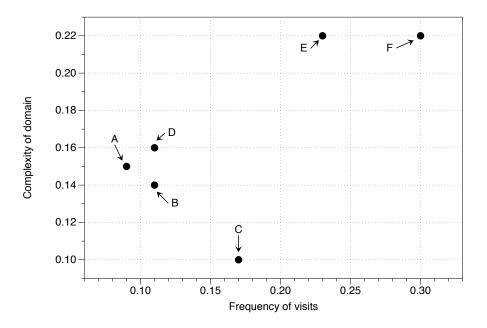


Figure 7: Plot of frequency of leeches' visits to domains $f(\cdot)$ and complexity of the domains $c(\cdot)$.

- 2. low complexity and moderate frequency of visits: domain C
- 3. high complexity and high frequency of visits: domains E and F.

Thus, we can state that a leech spends more time exploring floor layout templates with high complexity measured via number of corners.

With regards to differences in visits frequencies between domains with the complexity, our explanations are as follows. Frequency f(F) is 1.3 times higher frequency than f(E) because the domain F is closer to initial position of a leech (shown by arrow in Fig. 1). Thus a leech either turns into the corridor leading to rooms in the domain F, and then spends substantial amount of tie 'bouncing' there between rooms, or propagate to the end of main corridor and then turns into the domain E.

4 Discussion

We used living leeches in physical analog modelling of buildings exploration in scenario of limited visibility and no guidance. We studied patterns of leeches behaviour during 'unguided' exploration of geometrically constrained space where no gradients of attractant or repellents are present. The leeches were only relying on mechanical stimulation by walls of the template. We found that complexity of the building, even such simple one as measured via a number of corners in each part of the building, could provide a reliable estimate on how long time the leech will spend in the domain. Parts of the building with highest complexity are explored with higher degree of possibility. Having also in mind that part D of the examined floor corresponds to the "core" of the building with toilets, showers, communication rooms and store houses, i.e. rather small rooms, this is also rational in terms of evacuation decisions and strategy.

Future studies could be concerned with imitating search and rescue missions with leeches. We can represent targets, a leech search, by sources of physical stimuli which attract leeches. Potential attracts could include mechanical waves in water, temperature and chemical attraction. We have conducted scoping with leeches behaviour in thermal gradients. To form the gradient we immersed, by 5 mm, a tip of a soldering iron, heated to 70°C, in the water inside top corner room, in the domain A. Leeches were placed in the original position on the right side of the corridor (shown by arrow in Fig. 1).

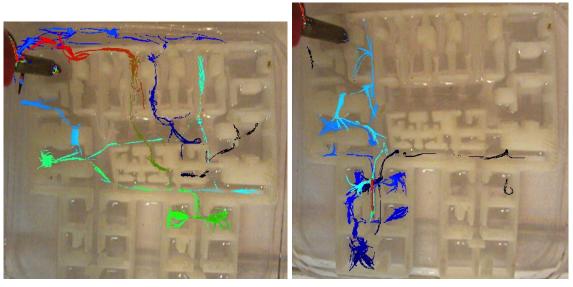
In five (5) of eleven (11) experiments a leech escaped from the template, in three (3) experiments the leeches moved into the domains E and F. However in three (3) experiments the leeches moved towards the source of thermal stimulation. For example, in experiment illustrated in Fig. 8(a), a leech propagated in domain D, explored domain B, briefly explored F and then moved to A. In experiment shown in Fig. 8(b) the leech propagated to domain E and spent a substantial amount of time exploring rooms there, then moved to domain A. In the experiment shown in Fig. 8(c) the leech first traveled back and forth between the domains F and C and then moved to domain A.

Future experiments could deal with rigorous analysis of thermal and vibrational gradients affecting the leeches propagation inside templates, and physical analog modelling of leeches templates or models of multi-storey buildings.

Finally, we do intend to run similar scenarios with humans for the exploration and evacuation of the real building under study. It is clear that in correspondence to the evacuation management and the human behaviour, as stated by Omer and Alon [46], two deeply rooted misconceptions should be further considered; the first one, that was termed *abnormalcy bias*, consists in underestimating the ability of people to function adequately in the face of disaster while the second, known as *normalcy bias*, consists in underestimating the probability of disaster, or the disruption involved in it (see Drabek, 1986, for a review on the prevalence of these biases and their deleterious influence in disaster management). In such a sense the differences and the physical disimilarities between the human and the biological entities like leeches should be further investigated even in simple almost ground truth scenarios like the ones introduced in this paper.

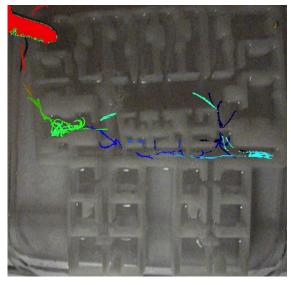
5 Supplementary materials

Videos of leeches: https://www.youtube.com/playlist?list=PLw-0L7RLQBmb8hn-xINBtAxhdN6Cq6VdU



(a)

(b)



(c)

Figure 8: Overlay of leeches movement in template with a source of thermal gradients.

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