Reaction-Diffusion Process Based Computational Model for Mobile Robot Exploration Task

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***Abstract*— This paper presents an exploration algorithm based on properties of reaction-diffusion models. The approach is based on our previous work on this topic, in which a novel path planning algorithm was developed providing competitive paths to standard approaches like smoothness of the found solution. In this paper, it is shown how the developed principles can be applied in exploration of unknown environment with a mobile robot. The presented approach represents a novel exploration strategy where the main decision logic is based on principles arising from the underlying dynamics of the reaction-diffusion systems.**

I. Introduction

A robotic exploration can be defined as a process of building a map of unknown working environment, where a mobile robot is requested to autonomously cover all reachable regions by its sensory system. Many approaches have been proposed since the first frontier-based approach introduced by Yamauchi [1]. A frontier represents a part of the known reachable environment that is incident with the not yet explored regions. Using an occupancy grid approach [2] to integrate new sensor measurements into a probabilistic map, frontiers can be found as freespace cells incident with an unknown cell, e.g., found using 8-neighborhoods, in a navigation grid map generated from the occupancy grid by thresholding the probability values into three classes: freespace, obstacle, and unknown.

The frontiers are suitable candidates to be a next robot goal towards which the robot can be navigated because they represent a reasonable expectation that unknown parts of the environment will be covered from them. Hence, the problem of exploration can be defined as an iterative procedure in which the next robot goal is determined (by selecting from all frontiers according to the considered optimization criterion) and then the robot is navigated to that goal while collecting new sensoric information.

Beside the greedy approach [1] that simply selects the closest frontier to the current robot's position as the next goal, more advanced exploration strategies have been proposed [3], [4], [5]. In [6], authors consider an expected information gain of goal candidates generated within a sensor range vicinity of the frontiers. Then, such candidates are selected in the next-best-view manner according to an ad-hoc defined utility function in which an expected area of the unknown environment being covered by the candidate is taken into account. On the other hand, authors of [7] consider an explicit on-line segmentation of the map into a set of clusters that have to be explored to avoid repeated visits of the same area, e.g., to explore particular rooms.

In this paper, we address the exploration task using a new algorithm based on dynamics and underlying principles of Reaction-Diffusion (RD) models. Although it is similar in many aspects with a regular frontier-grid-based approach, it provides a new way to generate the goal candidates. Moreover, we define the main decision logic as well as necessary supporting algorithms using principles arising from the spatial evolution of state variables described by the nonlinear RD model. Based on this effort, we can introduce computational building blocks that provide a groundwork for the definition of a computational model based on RD processes to address various robotic navigation problems. Such a computational model may provide a mechanism by which a hardware solution of the computation can be realized in a practical deployment within real robots.

II. Reaction-Diffusion properties of the computational model

The considered computational model is based on an RD process, where a diffusive process responsible for the spreading of the substances out in the space and a reactive process, in which the substances are transformed into each other [8], [9], [10]. In particular, herein the FitzHugh-Nagumo (FHN) [11] model is considered, which adopts the basic form:

$$\begin{array}{rcl} \dot{u} & = & \varepsilon\left(u-u^3-v+\phi\right)+D_u\triangle u \\ \dot{v} & = & (u-\alpha v+\beta)+D_v\triangle u \end{array}, \qquad (1)$$

where α, β, ϵ, and ϕ are parameters of the model.

The so-called bistable configuration is used, where null-clines (for $\dot{u}=0$ and $\dot{v}=0$ in the absence of diffusion) represent the shape depicted in Fig. 1, where intersections of both curves define the *fixed points* of the system, classified in stable (in green, towards which the concentration levels of the state variables (u, v) evolve naturally) and unstable (in red). Asymmetric configurations that constitute a simple method for modulating the relative stability of both stable states are depicted in Fig. 1c and Fig. 1b, where SS^+ and SS^- represent more and less stable states, respectively.

An interesting feature is that a system in a default configuration SS^- has a natural tendency to evolve towards SS^+ (the most stable state) if a small perturbation is introduced to the system. In addition, the frontwave driving this shift

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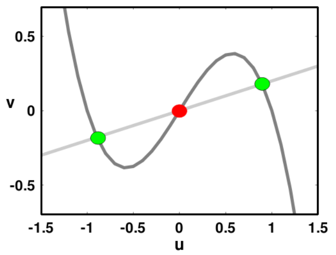
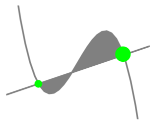
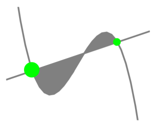


(a) General symmetric configuration for a bistable system. Both stable states are equally stable.



(b) propagation



(c) contraction

Fig. 1. Nullcline configuration, the green disks represent stable states (SS) and the red disk represents unstable state.

exhibits different properties than standard waves, an attribute of the strong nonlinear character of the underlying model. Another remarkable feature is the possibility of regulating its behavior in such a way that can reproduced frontwaves that annihilates after a collision, or conversely frontwaves that do not interfere after a collision, and therefore, remain static at the collision point.

This behaviour is one of the fundamental principles used for the path planning algorithm introduced in [10] and in the proposed exploration algorithm described in the following section.

III. Exploration Strategy Based on Autowaves

The proposed exploration strategy is motivated by the idea to exhibit a similar behaviour as regular frontier-based approaches; however, our intention is to use different underlying principles based on features of the autowaves, which allows us to propose a new concept of utility function. Thus, the proposed approach follows standard exploration procedure with the main loop consisting of the steps:

1) Integrate new sensor measurements into a map;
2) Determine goal candidates;
3) Select the next goal;
4) Navigate the robot towards the goal.

In the first step, a common approach based on the occupancy grid is considered. The second step is solved in a new way by using the frontwave propagation. Also the next steps are based on principles of autowaves. In particular, the next goal is selected using the same principles of the frontwave propagation. Finally, the step four is solved using the autowaves-based path planning [10] to determine the path to the goal along which the robot is then navigated.

Prior a description of the proposed candidates' generation and goal selection methods, particularities of the exploring units and working environment in the proposed autowaves-based approach are exposed:

- The environment being explored is considered as a set of objects and boundaries represented by their edges, all treated as binary information.
- The exploring unit shapes the environment within its sensor range without any awareness about the correspondence between objects or boundaries.
- Since all is treated as binary information, the operational space is split into reachable and unreachable locations.

The goal candidates are determined as a border of the currently known space of the environment; hence the current map is used as a medium for exhibiting the RD model dynamics. A frontwave (triggered from a bistable configuration with annihilation) starts at the robot position and evolves as an ordinary fluid, covering all the available space, which provides the boundary of the reachable area for the stable state of the system. Then, superimposing obstacles detected by the sensor system (e.g., laser range scanner) results in the reachable border to the robot, as depicted in the red profile shown in Fig. 2, where a complete obstacle is drawn just for an illustration because only edges of obstacles are sensed by the scanner.

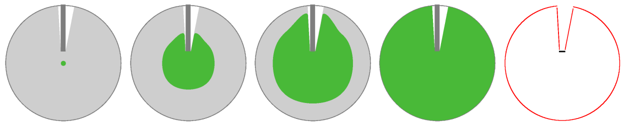


Fig. 2. A wavefront evolution in determination of the goal candidates. The light gray circular area corresponds to an omnidirectional sensor data (laser range scanner), whilst the dark gray rectangle in the top of the scene is an obstacle, which is completely drawn to improve clarity of the figure as only its edges can be sensed by the laser scanner. The green wavefront evolves from the robot position, covering all the discovered area till it reaches a static situation. The rightmost figure represents the final border reachable by the robot (depicted in red).

Once the border is determined, the next goal is selected using the autowaves-based path planning approach [10]. The border does not distinguish the unknown cells from the obstacles. An advantage of this planning is an ability to deal with noisy data (e.g., due to imperfect sensor measurements), see the referenced work for details.

A concept of utility functions for evaluating goal candidates aims to consider an expected benefit of the candidates to select the most suitable goal in order to improve performance of the exploration strategy according to the mission objective, e.g., to collect the map of the whole environment as quickly as possible. Such approaches usually combine the distance cost with expectations of exploring new areas [6], [3]. Contrary to these approaches, herein a different concept based on features of the frontwave propagation is proposed.

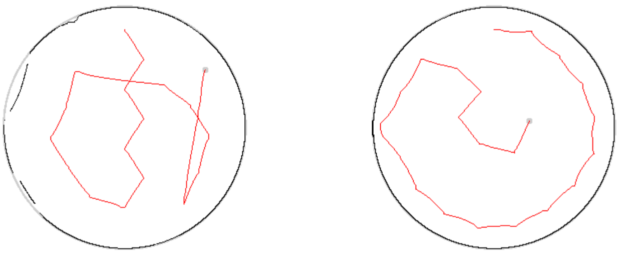
Fig. 3. Visualization of the utility introduction in the frontwave propagation for selecting the next goal. The gray circle represents a reachable area. The absence of obstacles allows the emerging frontwave to freely evolve from the robot position (slightly displaced downward relatively to the center of the circle) till the borders of the gray area, which in this particular case represents the boundary between explored and unexplored regions.

The dynamics of the underlying RD model allows to add an extra term representing additional information that is considered in the model evolution. Such an extra term is numerically represented as a matrix (an extra background with values from the range $bck \in \langle -2, 0 \rangle$) that selectively introduces delays in the wavefront propagation, and therefore, it can prioritize (bck=0) some regions over others, $bck \in \langle -2, 0)$. Thus, a local modifications of nullclines for the particular cells of interest allow to adapt a configuration that inhibits the wavefront propagation.

Considering a general background that introduces a general delay in the propagation, its reduction around object (obstacle) cells turns out into an increase of the wavefront propagation velocity around those places, leading to a basic boundary-follower exploring unit, which significantly reduces the tendency to perform multiple-visit to the same regions. A demonstration of such modified evolution of the frontwave is shown in Fig. 3, where the growth of the frontwave in the vicinity of the wall is clearly faster than in any other direction.

IV. Results

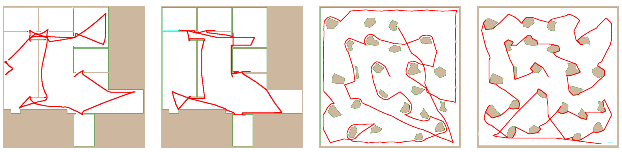
The proposed autowaves-based exploration strategy has been employed in an exploration of a simple circular environment to verify the proposed concept. An example of the robot exploration path from which the whole environment is explored (covered) using an omnidirectional laser scanner with the sensing radius ρ=5 m is depicted in Fig. 4.



(a) open-space preference (b) wall-following preference

Fig. 4. An example of exploration strategies based on different settings of the computational model.

Based on these results, two additional environments are considered to verify feasibility of the proposed approach. In addition, the greedy exploration [1] approach (using all frontiers cells as goal candidates) and the TSP based approach [5] are used to provide a preliminary overview of the proposed strategy behaviour. In these strategies, the next goal is determined after performing 7 navigational primitives as it is recommended in [12].



(a) *Autowaves*, ρ=7 m, L=110 m (b) *Greedy*, ρ=7 m, L=93 m (c) *Autowaves*, ρ=5 m, L=332 m (d) *TSP*, ρ=5 m, L=315 m

Fig. 5. An example of found solutions using different exploration approaches. The length of the final exploration path is denoted as L.

Selected exploration paths are shown in Fig. 5. Here, it should be mentioned that in these exploration scenarios, the proposed autowaves-based exploration approach has not been specifically tuned; hence, there is a possibility for an improvement of its performance. Regarding these preliminary results, it seems that the proposed exploration strategy provides competitive solutions to the standard approaches.

V. Conclusions and Future Work

In this paper, a novel exploration algorithm based on underlying principles of a reaction-diffusion model is presented. The proposed approach can be considered as a direct extension of our previous work, which introduced an autowaves-based path-planning method, and was found to exhibit interesting properties in comparison to standard approaches. Although the presented results can be considered as preliminary, they indicate feasibility of the proposed autowaves-based exploration and provide a premise for at least a competitive performance with the current state-of-the-art exploration methods. Moreover, the algorithm provides basic building blocks of a computational model for a mobile robot exploration solely based on an RD process, which is a subject of our future work.

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