2012 IEEE Sixth International Conference on Self-Adaptive and Self-Organizing Systems

Gradient-based Self-organisation Patterns of Anticipative Adaptation

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***Abstract*—In this paper we conceive new self-organisation mechanisms to enhance the *Gradient* self-organisation pattern with anticipative adaptation abilities. We ensure that the problem of retrieving a target of interest in mobile environments is solved by proactively reacting to locally-available information about future events, namely, the knowledge about future obstacles (e.g., expected jams or road interruption in a traffic control scenario) is used to compute alternative and faster paths in an emergent way.**

I. Introduction

Recent studies on self-organisation identified existing and new patterns to design computing applications featuring desirable properties of adaptation and robustness to unpredicted changes in the environment, such as human interaction, network mobility and faults, events in the physical environment. As a reference, we consider the work in [1], in which a catalogue of patterns for self-organisation is introduced. Following a series of work in self-organising coordination [2], [3], such a catalogue uses a paradigm of chemical-like transformation rules (manipulating information items residing in the network nodes) to specify pattern behaviour and pattern combination. This catalogue is organised in layers (see Figure 1): low-level patterns achieve basic self-organisation mechanisms (Spreading, Aggregation and Evaporation), middle-level patterns are used to spatially organise information (Gradient [4]), and high-level patterns exploit such information to achieve individual or social goals in a multi-agent system (Quorum Sensing, Chemotaxis, Morphogenesis)—e.g., Chemotaxis allows an agent to navigate a gradient distributed data structure to reach its source node even in the case of a very mobile and dynamic environment. An important role is hence played by the Gradient pattern, a key brick of self-organisation mechanisms that is designed to provide optimal paths to roam a distributed system even in the context of very articulated environments (a building with rooms and corridors, or a traffic scenario) and by dynamically adapting (namely, self-healing) to unpredicted situations such as sudden road interruption. This pattern hence finds numerous applications, including hop-by-hop communication in a wireless network, and physical items retrieval in situated applications such as those of pervasive computing [5], [6], [2].

We note that – to the best of our knowledge – existing techniques studied for Gradients (see e.g. [4], [2], [3]) tackle only present-awareness, that is, they adapt to events only at the time they occur. In this paper, we are instead concerned with how Gradients can be equipped with *anticipative adaptation*, namely, how they can take advantage of the local availability of information about future events, once this has been provided by some component in charge of situation recognition [7]. Our idea is to use such a knowledge in advance to stretch and deviate certain parts of a Gradient structure so as to promote alternative paths that could be longer, but guarantee to eventually circumvent any forbidden area so as to reach the target in shortest time. Following the self-organisation approach, this will be realised in an emergent way, relying only on local interactions and without any supervision. Example scenarios where this mechanism can be useful include traffic management, to tackle pre-scheduled road constructions, availability of historical formation about traffic jams in certain areas of a city, known timing of opening bridges or railroad crossing, and so on. It can also be used in crowd steering applications based on signs appearing in public displays [3]: e.g., in a large exhibition center the scheduling of popular and typically crowded exhibitions can be considered with the goal of anticipating and preventing the formation of crowds.

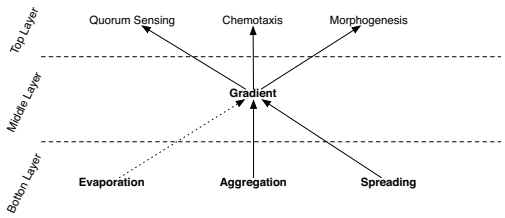

Figure 1. Gradient-based self-organising patterns [1].

The remainder of this paper is organised as follows. Section II outlines the concept of self-organisation pattern developed in [1] and which we build upon; Section III discusses analysis, design, and early evaluation, of the mechanisms needed to support the Anticipative Gradient pattern; and finally Section IV concludes with a discussion of related and future works.

II. Self-organisation Patterns

To make self-organisation mechanisms systematically applicable, different recent works [1], [8], [9], [10] have focussed on proposing descriptions of those mechanisms

978-0-7695-4851-7/12 $26.00 © 2012 IEEE
DOI 10.1109/SASO.2012.25

under the form of catalogues of software design patterns [11]. We here focus on the framework described in [1], where a set of bio-inspired self-organisation mechanisms are analysed, classified and described, identifying their relations and the recurrent problem they solve. As underlying computational model, it is assumed a network of computational devices (or nodes), each interacting with a limited neighbourhood and storing *annotations* containing information about the environment, its events, and agents residing locally. Self-organisation mechanisms are there modelled by simple transformation rules resembling chemical reactions working over such annotations—mimicking service frameworks such as the pervasive ecosystem approach [12]. In a very abstract form, such rules manipulate "tuples" $\langle L, A\rangle$, formed by pairs of a location (node) L and annotation A stored in it, and are of the kind $\langle L_1, A_1\rangle, \ldots, \langle L_n, A_n\rangle \xrightarrow{r} \langle L'_1, A'_1\rangle, \ldots, \langle L'_m, A'_m\rangle$ where: *(i)* the left-hand side (reagents) specifies which information is involved in the transition rule, and which will be removed as an effect of the rule execution; *(ii)* the right-hand side (products) specifies what is accordingly to be inserted back in the specified locations; and *(iii)* rate r is a rate, indicating the speed/frequency at which the rule is to be fired, namely, its scheduling policy.

A result that comes out from the introduction of those patterns is that most high-level algorithms presented in the literature can be designed and implemented on top of the Gradient pattern. This can be understood as a computational field [13], [5], [2], namely, a distributed data structure mapping each node of the network (or of a subpart of the network) to some (possibly structured) value. Specifically, a Gradient is created out of a *source*, and maps each node of the network to its estimated distance from the source, along a dynamically-computed optimal path. Technically, this is achieved by relying on *gradient annotations* carrying the estimated distance (0 in the source), *spread* to a neighbour with increased distance (the entity of such increment could be simply 1 for hop-counter distance, but can also estimate physical distance or expected travelling time), and *aggregated* in each node so as to retain the one with more recent information and minimum distance value; *evaporation* is then used as an ageing mechanism, e.g., to dispose a Gradient when its source is removed. Interestingly, the Gradient pattern can be designed to automatically self-heal to changes in the topology and to movement of the source [4].

As a main example of upper-level pattern exploiting Gradient, Chemotaxis is about making a mobile agent (or some information) descending a Gradient data structure so as to reach the source from any node the Gradient structure has reached. This is achieved by making the agent continuously reading the estimated distance value as reported in the Gradient annotations stored in its neighbourhood, and then moving towards the node exposing minimum distance – the source is eventually reached by construction. This pattern finds applications in long distance communications, or in physical items retrieval in situated applications such as those of pervasive computing [2].

III. Anticipative Gradient

In this paper we conceive new self-organisation mechanisms built upon the above Gradient pattern to tackle anticipative adaptation, namely, ensuring that the retrieval of the gradient source proactively reacts to available information about future events, namely, impossibility of transiting across a given area—e.g. modelling interruptions of roads in traffic control applications. In this section we first motivate and analyse the problem, then elaborate a solution based on a combination of mechanisms related to the Gradient pattern, and finally check the general correctness of the result by some simulation. Our solution is based on the informal description of chemical-like transformation rules following the framework described in previous section [1]. A formal incarnation in the framework developed in [3] has been developed and used for the simulation results we shall present, but its description is neglected in this paper for the sake of space.

A. Motivations and problem analysis

A basic application of the Gradient pattern is to steer a requester from its current location to the Gradient's source location—namely, what is called Chemotaxis pattern in [1]. Such a requester (which we here generally refer to as an agent) can either be a mobile software agent roaming a network to find proper information, a person guided in a complex environment by signs dynamically appearing in its smartphone [14], a car which is given traffic control suggestions through its navigation system, or an information item directed to the target of a communication [2]. It is quite standard to make the Gradient field adapt to contingencies as soon as they appear: for instance, interruption of a road can reflect into a change of the network topology, leading to the automatic recalculation of the Gradient structure to identify a new path towards the target of interest. Following that line, in [3] it was studied how dynamically-formed crowded areas can be perceived as areas to be circumvented by other people roaming the environment.

We address the design of a different mechanism which, to the best of our knowledge, has never been considered so far: how Gradient-based self-organisation mechanisms can be extended to deal with the case in which in some node(s) there is knowledge about an event that will occur there in the future and prevent/modify the ability of an agent to transit across the node. Taking advantage of such information, one could think of a strategy to spread this information around such that – in an emergent way – the Gradient can somewhat deviate to anticipate the effect of the future event, possibly promoting a path that could be longer but guarantee to

circumvent the forbidden-area eventually reaching the target in shortest time. There are several example applications for one such mechanism, tackling the availability of information about future road constructions, statistic formation of traffic jams in certain areas of a city, timing of opening bridges or railroad crossing, scheduling of popular and typically crowded exhibitions in a museum, and so on.

We aim at designing a solution that is not tight to a specific application context, but has the same level of generality of the Gradient pattern. As such we assume – in continuity with the basic hypothesis used for the Gradient pattern – that the environment is densely covered with computational nodes hosting annotations and forming a topology reflecting the structure of the environment (and hence its ability of being roamed by agents). We also assume that in each node estimated "distance" to all neighbours is available: such a distance should measure the expected average time needed for an agent to move from one location to another—here we will rely on general "time units" without any correspondence with a physical time. The underlying middleware is in charge of keeping this information lively updated, such that formation of crowded areas are automatically reflected into a higher distance of the link between two nodes, thus making a path including such a link less appealing—accordingly, we will not consider crowd information further in this paper. We hence refer to *agent-speed* as the non-uniform ratio between physical distance and estimated transiting time at each location.

In some node of the network there could be some (future-aware) situation recognition component [7] in charge of intercepting a future event, namely, what happens and when. In this paper we shall focus on events concerning impossibility of transiting across the node, expected in the period of time in the future in between Ts and Te ($Ts < Te$) time units from current time. Our basic strategy, detailed below, is to make information about such (possibly multiple and overlapping) events spread around, and suitably combine with a Gradient created to reach a target of interest. The result of such a combination, what we call an Anticipative Gradient, will be used by agents to navigate towards the target of interest along optimal, dynamically computed paths taking in consideration those future events. According to the self-organisation style, such mechanisms will be based only on local interactions, and will be carried on without any global supervision.

B. Spatial structures

1) Horizon Wave: A first component in our strategy is the advertisement of a future event (FE). We call FE area the set of nodes that will host such an event. Advertisement of the FE needs not require full-space and -time propagation, but – at a given time – it should reach only the set of nodes that might be concerned by the FE, namely, those from which an agent moving towards the FE area would actually reach

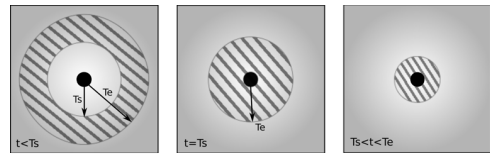

Figure 2. Horizon Wave pattern, with its shrinking dynamics in evidence.

it when the FE actually occurs. In a sense, the set of points in space and time that should be advertised resembles the notion of event horizon in physics, though it is here located in the past and propagates at the agent-speed. This is why we refer to this pattern as Horizon Wave (or Wave for short).

We consider for simplicity a uniform and continuous 2D environment, allowing us to better grasp the behaviour of the proposed mechanisms. There, a Wave defines a (circular) crown-like region of space that, as time passes, shrinks into the FE area at the agent-speed, until completely disappearing as shown in Figure 2. Agents outside this spatio-temporal data structure needs not be concerned about the FE.

This spatial structure can be obtained on top of the Gradient pattern as follows. We let the FE area be source of a Gradient, and any of its annotations (as diffused by the spreading process) carry information about Ts and Te. A node of the network is then inside the Wave if $Ts \leq D \leq Te$, where D is the node's distance from the FE area as reified by the Gradient annotation available locally.

2) Gradient Shadow: In order to understand whether an agent should actually care about circumventing the location of an FE, it is also important to consider its direction and target. Let's focus on the Gradient generated by a target p that an agent is directed to. We should properly tag the portion of such a Gradient from which an agent, while steered towards p, would eventually transit across an FE area. Such a portion is here called Gradient Shadow (or simply Shadow), for it recalls the shadow that the FE area would cause if it were an opaque object and the gradient source would be a source of light. Figure 3 emphasises that the Gradient we create out of a target of interest should be able to possibly tag different, overlapping Shadows, reflecting the existence of many FEs around.

The main strategy to create this spatial structure amounts to let Gradient propagation track, with a proper tag in the annotation, when it crosses an FE area: by successive propagation the tag will be reified across the whole Shadow. Most specifically, this is achieved by a new chemical-like rule, matching two annotations located in the same node: the gradient annotation spread from a target p and the annotation of a FE e. The effect of the rule is to update the former annotation, adding e to the list of "tags" it should carry. Additionally, we update the aggregation law such that only Gradient annotations having the same list of tags will be aggregated. In the case of a single FE e, hence, in each node we will possibly have both the annotation tagged by e

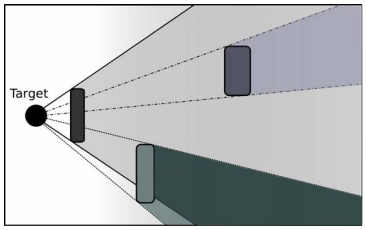

Figure 3. Shadow spatial structure with overlapping Future Events

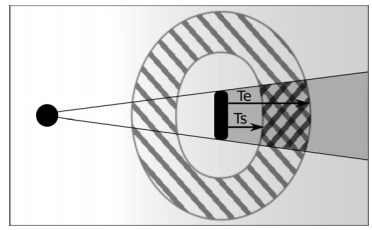

Figure 4. Warning spatial structure as intersection of Wave and Shadow

and the one with empty list of tags, which respectively carry information about a route that crosses an FE and one that circumvents it. In the case of multiple FEs, all combinations will be automatically generated.

Hence, the Shadow structure created from target p due to FE e is defined as the set of nodes whose distance to p along a path crossing e's area is smaller than the one circumventing it, namely, nodes having an annotation tagged with e carrying a smaller distance value that any annotation that is not tagged by e.

Again, while targeting a given point of interest, only agents located in a FE's Shadow should be concerned about the FE, since outside that area an agent would by construction be steered to the target without crossing the FE area. Note that differently from the Horizon Wave pattern, a Gradient Shadow is mostly a static structure, immutable over time: of course, it can still be subject to automatic changes due to mobility of the topology, relocation of gradient source, or interception of new future events.

3) Future Event Warning: Now that these two basic bricks have been defined, it is easy to identify their intersection as the portion of space – which we call Future Event Warning (or simply Warning) – in which the Gradient has to be deviated to anticipate the FE. More generally, given a target of interest p, and a set $e_1, .., e_n$ of FEs, let the Global Wave be the union of the Waves of all e_i, then the Warning area is simply obtained by the intersection between p's Shadows as created by $e_1, .., e_n$ and the Global Wave. In our computational framework this area is formed by the nodes featuring the gradient annotation of a target p tagged by an FE e (Shadow), as well as the gradient annotation of FE e whose distance is in between Ts and Te (Wave).

An example of such a structure for a single event is shown in Figure 4. Considering only one event e, this area has the shape of a crown sector, it is located on the opposite side of e with respect to the gradient source, and it moves towards e until vanishing.

4) Anticipative Gradient: We now define the most important self-organisation pattern emerging from the combination of the above ones, namely, what we call the Anticipative Gradient. Starting again from a target p, and a set of future events $e_1, .., e_n$, this is identical to a standard Gradient outside the Warning area, since there agents can be steered to p without any special management. Inside the Warning area of an FE e_i instead, distance and orientation values in each node should reflect the optimal path among the two following alternative: the one crossing e_i and the one circumventing it.

An additional caveat is how we can compute the actual time-to-destination (i.e., distance) of a node n in the Warning area along a path crossing an FE e—since using that path will make the agent experience the obstacle in the future. A possibility for an agent would be to wait in n until it is outside the Warning area and then move towards e and then to p. Alternatively, it could immediately move from n towards e, and be stuck there until the Wave is over—it can be shown that the strategy of circumventing the FE area instead of staying stuck is never winning over the one finding a path circumventing e since the beginning. In any strategy, the time-to-destination is the one obtained without considering e (T), plus a *waiting distance* (T') measuring the distance of n to the outside margin of the Wave (namely, the waiting time the agent would be forced to)—see Figure 5. Note that in the case n is simultaneously inside many different Warning areas, the distance value should be increased by the waiting distance computed for each of them.

Figure 5 also qualitatively depicts what are expected directions in a Warning area. On the one hand, near the end of the Wave and in central position there is relatively little advantage in trying to circumvent the future event location, for the strategy of moving towards the FE anyway is winning. Hence, the orientation is towards the FE. In that region, we expect a rather uniform time-to-destination. On the other hand, at the beginning of the wave and in lateral positions of the Warning area the steering service will likely redirect an agent laterally outside the Warning zone to bypass the FE area.

More precisely, the Anticipative Gradient can be created out of two additional laws working as follows. The first law simply takes the Gradient annotation generated from a target, and clones it into a unique new annotation for the Anticipative Gradient: at this stage the two annotations will report the same distance D from the source. The second law matches the annotation a of an Anticipative Gradient as created above with the annotation w of the Wave of an

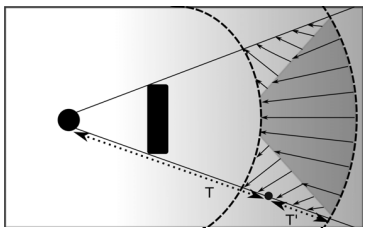

Figure 5. Anticipative Gradient pattern (and "waiting distance" T').

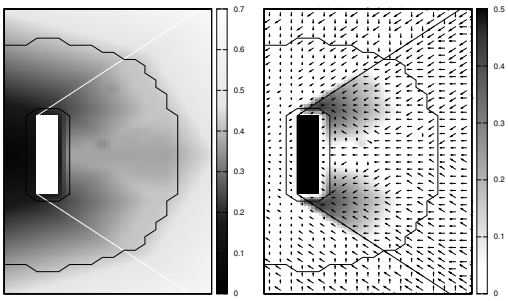

Figure 6. An Anticipative Gradient case: (Left) estimated distance normalised by the maximum value; (Right) time-to-destination improvement factor and steering direction.

FE e: its result is that e is removed from the list of tags in a, and a's distance is increased by e's waiting distance as discussed above, computed as $T_e - D$. Note such a law would iteratively fire to match a with the waves of all active (overlapping) FEs, until a's list of tags is emptied.

The neat result is that the Antipative Gradient is identical to the standard Gradient outside Warning areas, it instead selectively reports augmented distances in Warning areas, such that following the route towards nodes with minimum distance to the target always guarantee to efficiently avoid obstacles appearing in the future.

C. Simulations

We checked the basic correctness of the proposed self-organisation pattern by simulation, conducted using ALCHEMIST [14], [15], a prototype simulator extending the typical engine of a stochastic simulator for chemical reactions with the ability of expressing structured reactions (namely, where chemicals can have a tuple-like structure and reactions apply by matching) and of structuring the system as a mobile networked set of nodes. Apart from performance issues – ALCHEMIST scales better than other simulators like Repast [16] due to optimised data structures used to schedule chemical-like reactions [17] – ALCHEMIST simplifies the task of producing correct simulations since there is a small abstraction gap between simulation code and the proposed rule language.

Figure 6 (left) shows a pictorial representation of how the Anticipative Gradient looks like in a simulation of a

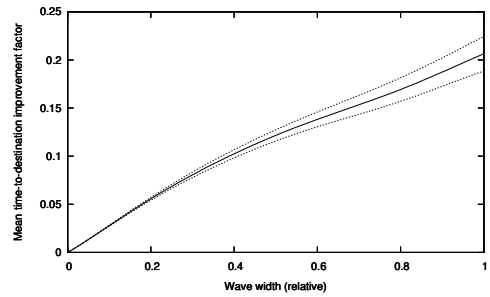

Figure 7. Mean time-to-destination factor (and standard deviation) in the Warning area, measured with different widths of Horizon Wave (normalised to grid size).

2D grid of 60x30 nodes, with a white-coloured rectangular-like FE. Figure 6 (right) shows what would be the right direction proposed at that time in each node. The analysis of these data confirms the expected qualitative results, in analogy with Figure 5. Namely, in the Warning area there is a whole triangle-like sector in which the estimated distance is higher (lighter colour) and constant—due to the waiting-time an agent has to experience. There, the proposed direction does not circumvent the FE. Instead, in the upper and lower border of the Warning area the Anticipative Gradient would tend to steer an agent away from the FE. Figure 6 (right) also shows what is the relative improvement an agent would experience when starting from the different locations of the network thanks to the anticipation of the future event. It ranges from a 50% in nodes near the left border of the Warning area to a 0% in nodes outside the Warning area.

Figure 7 shows what is the average (with standard deviation) improvement for nodes in the Warning area depending on the width of the Wave. Clearly, there is a greater improvement in using the Anticipative Gradient pattern in those cases where the future event lasts longer, namely, with higher width ($Te - Ts$) of the Wave.

IV. Conclusions and Future Work

Adaptation is a big challenge in the context of large-scale distributed systems, such as pervasive and ubiquitous service systems [19]: "proactive adaptation" [20] (or anticipative adaptation) has been recognised as crucial to avoid distressing situations before actually encountering the problem, so as to provide more effective services.

Previous works on nature-inspired self-organisation in the context of distributed systems do not challenge anticipative adaptation. Most literature addressing anticipation focusses instead on multi-agent systems (MAS), introducing "anticipatory agents" with high level reasoning capabilities, scheduling actions based on beliefs about the future [21]. To the best of our knowledge, these approaches do not discuss the notion of space in decentralised systems, where sharing information requires advanced dissemination mechanisms.

In order to tackle anticipative adaptation at the self-organisation level, in this paper we propose a new set of gradient-based mechanisms in the form of spatial structures called Wave, Shadow and Warning, that compose together to build the Anticipative Gradient. The main application is in the context of steering services (e.g. traffic control or crowd steering), which can become able to rely on local predictions about future events to anticipate alternative routes that circumvent potential sources of jams. The proposed solution is here informally specified in terms of chemical-like rules [3], directly leading to a simulation platform which has been exploited to check the correctness of the proposed approach. The framework we adopted to structure annotations and their manipulations by chemical-like rules is largely inspired by the work in the context of pervasive service ecosystems [12], finding an incarnation language as developed in [3].

Among the many future works tuning our work towards real-life applicability, we aim at generalising the proposed patterns to understand whether similar combinations of mechanisms can be applied to different problems and scenarios in environment-based agent-based systems [18].

ACKNOWLEDGMENTS

This work has been supported by the EU-FP7-FET Proactive project SAPERE Self-aware Pervasive Service Ecosystems, under contract no.256873.

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