TOWARDS A COMMON UNDERSTANDING OF THE DIGITAL PHEROMONE

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Abstract: In this paper we critically evaluate the research on digital pheromones to date and conclude that the wide variance in the understanding of what a digitised pheromone is serves to defocus research. We examine the classical pheromone-use algorithm, the ant algorithm and conclude that as such it has not been proven feasible for practical use. By examining the failure of proposed applications we derive an application where pheromones appear to offer added value. On critically evaluating an initial implementation we note its success but point out that lacking the understanding of biological pheromones serves to hinder research in digital pheromones in general and bio-inspired robotics in particular. We propose a set of rules and urge researchers to critically evaluate them.

1 INTRODUCTION

The general conceptual framework around this position paper is the argument that bio-inspired algorithms in general and pheromones in particular, which have been suspected of bringing efficiencies to real-world problems, are not as simply transferred to real-world problems as the state of research implies but require substantial applied research which leads to a re-evaluation of previously held opinions. In particular the paper presents the argument that the state of the art in pheromone research has not brought forth any applications that can reasonably use pheromones and that the actual implementation of these pheromones are so far removed from the biological understanding of the term as to mutate to mere marketing slogans. We present an application which we believe to be as real an application as to deserve the term pheromone but show that even then it can be argued that the notion of digital pheromone ought to be qualified by quotation marks.

The paper is structured accordingly – we begin by examining the biological definition of a pheromone before critically reviewing the current state of research on the digital variant of the topic. We evaluate known use cases and construct what we consider to be a viable use case and defend this principle. We then presents preliminary result of an implementation and draw the conclusions which are then discussed in the broader context of this argument.

Final conclusions follow with an outlook on further work.

2 PHEROMONES

2.1 Natural Pheromones

Pheromones are well described (Wyatt, 2003) but in summary are known to science as complex organic compounds, and mixtures thereof, excreted by animals and insects for message passing purposes. Pheromones are generally, but not canonically, classified by the reaction they invoke in receptors. Propagation is by diffusion, accelerated by velocity and concentration of excretion as well as the intrinsic cohesion and medium composition properties of the carrier (air, water). Reception is for homogeneous message passing, apparently, an exact science in that the receptors can be very discriminating with respect to direction, in some cases in three dimensions, and distance, some moths and butterflies can famously detect potential mates from some 10 km away. For heterogeneous communication all or a subset of the information intentionally transported may be, either intentionally

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or unintentionally detected by other species.

What is known is that certain animals will re-orientate their physical position according to whether they wish to maximise or minimise the reception of pheromones, what isn't so well discussed is whether – especially with airborne pheromones – the act of excretion takes advantage of ambient media conditions. There are simple examples to suggest this is sometimes the case, dogs and lamp posts spring to mind. More complex examples quote bees which excrete pheromones and accelerate movement of their wings in order to facilitate distribution (Reinhart, 2009).

2.2 Fundamentals of Technical Pheromones

From a technical point of view pheromone transmission represents connectionless wireless transmission, stochastic propagation with signal and media dependent dispersion and attenuation. Reception results in concentration dependent pulse streams. Signal filtration is at point of reception.

Given that technical communication systems depend on some form of determinism with respect to probable area of distribution of transmitted signal, when using pheromones we may assert:

Rule 1: Technical implementations of pheromones must show some awareness of ambient media conditions. If it is not otherwise possible digital pheromones shall implement some time based degradation profile.

Rule 2: It is acceptable for mobile units wishing to excrete or receive pheromones to deviate from their current path of motion to do so.

Rule 3: Pheromones serve for excreters and receptors to interact within temporal and geographic limits defined by the medium of choice.

As a complex chemical, sometimes a mixture thereof it is the presence of a pheromone that denotes the primary information value. The secondary information is given by the concentration, or the rate of change of concentration.

3 TECHNICAL IMPLEMENTATIONS OF PHEROMONES

3.1 "Virtual" Pheromones

Payton et. al's. work is well cited with respect to their pherobot project during which he coined the phrase "Virtual Pheromone". (Payton, 2001, 2003, 2004) They envisioned the search and rescue use case and whilst they begin promisingly, detailing some of the simpler characteristics of pheromones, it becomes hard to reconcile priority transmission, message passing and data request primitives with the concept of a bio-inspired pheromone. Although the term "Virtual Pheromone" found use with other researchers, in essence his solution reduces to a mixture of a directed transmission/re-transmission service combined with elements of embodied and situated communication.

The message complexity suggested by Payton et.al. was vastly reduced by Campo et.al (Campo, 2010). to three message types who, following other authors (Ducatelli, 2008), conceptualised message passing as an ant which laid pheromones along a chain of robots whilst being passed along this chain by the robots themselves. The concept has much merit, but is an abstraction removed from the physicality of laying down a trail and acting on it like the bio-inspired counterparts.

3.2 Pheromone Storage

Storage of these imagined pheromones is always an issue. Most research that requires a bio-inspired model and a pheromone tends towards research in swarm robotics which in turn generally means that short and medium term coordination is the task to be solved by the use of these pheromones. Meng (2008). built a map of swarm participants and their respective pheromone densities. Borzello and Merkle (2005) deposit a "pheromone", whose structure is unclear, on an uncompleted task by a robot who then attempts to find another task leaving the next random-walking robot to chance across the task and attempt to complete it. The work, located solely in the virtual world, attempts to use the ant algorithm in an attempt to prevent task-deadlock in multi-robot cooperative scenarios. As such the pheromone loosely corresponds to a signal pheromone, a pheromone designed to trigger a short-term behaviour alteration. In this case the pheromone triggers a state change in a state machine, the behavioural pattern itself is not changed and the pheromone does not serve to attract the mobile robot nor does it induce any kind of cooperative behaviour making it difficult to consider it a "proper" pheromone. Both Susnea et.al (2009) and Gunzinger and Pffifner (2008) use a central server to map the pheromones onto virtual space and provide these details to real-world requesting robots.

The use of air as a medium has also been researched. Kuwana et.al, (1995) in earlier work attached live moth antenna to a mobile robot to follow moth pheromones. A practical application of this technique would however depend on both keeping the moth antenna alive over a longer period of time and being able to generate the moth pheromone in some manner. Russell and his researchers (Purnamadjaja, 2004) tackled this problem by using inorganic chemicals and gas sensors for pheromone generation/detection. Fujisawa et al. (2008) use ethanol as a pheromone.

There are other deposition media considered such as ink on substrate (Svennebring, 2004) or UV on phosphorescent coating (Mayet, 2010) but whilst general feasibility may have been shown these do not represent solutions that are likely to be taken up by industry. Several researchers including Mamei et.al. (2005) Heiranto (2009) and Doran et.al. (2009b) have experimented with the idea of using RFID tags. Heiranto concentrates on imagining a floor of RFID tags whilst Doran and Mamei imagine discretely positioned tags within a building.

3.3 Pheromones and Methodology

Interestingly enough Gunzinger found that the ant algorithm was, for his particular scenario noticeably less efficient than the Dijkstra algorithm in finding a path with the help of pheromones but unfortunately failed to quantify this. The use of a bio-inspired model in conjunction with a mathematical algorithm is not new and but does lead us to several questions.

The first is as to the general methodology concerning the use of bio-inspired models. The author has experienced in other projects, notably the implementation of fish swarming algorithm that the algorithm appears to need continual refinement which is generally mathematical in nature, before being implementable in hardware. This may be due to the fact that a bio-inspired algorithm must generally be expressed mathematically before initial implementation therefore further refinement is by default mathematical and the Gunzinger case is merely the extreme case where the refinement of a bio-inspired algorithm is simply not efficient given known mathematical alternatives. It may also be due to the fact that researchers are trained to research in this way and that a lack of methodological flexibility precludes the discovery of alternatives. In either case it would thus appear probable that the act of observation and expression of a bio-behaviour in mathematical terms causes the algorithm to lose the robustness that the observer wished to capture in the first place.

Also, by observation, the author has noticed that the necessary input to enact a behavioural pattern generally cannot be solely received from one sensory input - is a second or third sensory input is required. For example fish schooling can be simulated by using an interpretation of the lateral line but the creation or breakup of a school requires either a short-cut using either, for instance, a random walk or optical species recognition. Given that neither a real nor artificial fish will grow and utilise eyes solely for swarming purposes but as Lichtensteiger (2005) shows, albeit for flies, artificial evolution of eye morphology leads to single-use optimisation. It is unfortunate he omitted to test quality of second and third priority tasks. These observations inevitably lead to the question as to whether, and if so with what methodology, behavioural patterns can be isolated and implemented whilst avoiding a holistic approach to robot development.

3.4 Implementation Architectures

Controller architectures also play an important role. In many experimental systems standard controllers using some form of state machine are used. Whilst state machines are often used in embedded systems mapping a behavioural pattern into a state machine is the engineering equivalent of expressing an observed algorithm in a mathematical form, the essence is bound to get “lost in translation”. The use of state machines to switch between behavioural patterns has, according to the authors research, not yet been researched, but given the experience at the sensor level where some convolution of sensor inputs produces an output, it is unlikely to work very well. Other controller architectures use neural networks and evolve behaviour. Neural networks have so far, by and large, failed to impress industry due to the fact that training is lengthy and is both non-deterministic and non-reproducible in output. Whilst self-modelling, as shown by Bongard et.al. (2006), is promising, it will be some time before we see such architectures implemented.

Ants are relatively easy things to conceptualise but, the drive towards cheap microbots notwithstanding, robots cost money, ants don’t and a lost ant won’t be missed whereas a lost robot will. Therefore the task that the robot must fulfil should be equivalent to the complexity (and by proxy cost) of the robot. If we orientate ourselves to animals which can be used in various scenarios then we need something at least of the relative complexity of a dog (Doran, 2009a). On the other hand there doesn’t seem to be any reason why one can’t borrow the sensor system of an ant and graft it onto a robot dog.

Given a pheromone is intimately connected with a behavioural pattern (searching for and identifying pheromones) and the switch between behavioural patterns this must be reflected in the controller architecture. Therefore the robot designer must be able to combine the behavioural patterns of various models to make one robot.

In conclusion and summary:

Rule 4: A pheromone may be used to switch from one behavioural pattern to another, or prevent such a switch taking place, should it be present in sufficient concentrations.

4 DEFINING AND EXPERIMENTING WITH A REAL-WORLD USE CASE

4.1 Deriving the Scenario

Gunzinger's work represented an attempt to assess whether the ant algorithm could be used for real-world navigation scenarios. What it clearly showed was that ant type algorithms are wildly inefficient if the environment is even only partially known. On this insight it is possible to narrow down the purpose of an autonomous search by a robot to the case when a known route is blocked and a second or third passable route must be found. Formally this problem can be expressed as the robot knowing a route at time t0 which is invalid at time t1, discovered by the robot to be invalid at time t2 and that a new route is discovered by the robot at time t3 with $t0 < t1 < t2 < t3$. The optimisation an ant routing algorithm can achieve is by directing the following robot to the correct route without it going through the discovery phase already performed by its predecessor.

4.2 Deriving the Use Case

Landhuis and Terwellen's work (2010), which attempted precisely this, plays an important part in the development of this papers argument. Based on the premise that mobile robots making deliveries on known routes may be blocked for periods of time long enough for it to be more efficient for the robot to spend its time searching for a new route, the work also presumed that the robot would be given tasks, and a route, by a job server but would not have continuous contact with the job server via a house-intern WLAN network and therefore requires partial autonomy. Given a set of RFID tags which, being cheaper by far than a WLAN access point and can be spread redundantly across the corridors of a building, can be used to store pheromones, a robot searching for a new route can deposit re-enforcement or detractor pheromones depending on whether it is tracing or re-tracing its tracks. Whilst Gunzinger (and Payton) had to invent pheromone types to fulfil their respective tasks – and hence severely compromise the quality of their conclusions, Landhuis was able to call on the precedent of the Pharaohs Ant (Robinson, 2008) which, unlike other ant species, deposits detractor pheromones to cancel out re-enforcement pheromones. Given the scenario that the robot used a local, non recognising, navigation (in this case ultrasound transducers) and an extended Braitenberg architecture (Lambrinos, 1995) with three active inputs, the job/map, the local navigation and the pheromones, Landhuis and Terwellen were able to show that in the case of a blockage in the parcours the use of pheromones was not inefficient with respect to a robot always connected to a server or one which returned to base when faced with a blockage. Landhuis and Terwellen were also able to show that using pheromones to mark routes brought efficiencies with respect to using random walk methods.

Figure 1: Simulation results for a robot's response to a blockage. On job 3 a robot responds to a blockage by either returning to base (red), or finding another route with the help of RFID pheromones (green). The blue line shows the response if the robot is always connected to a server.

Most importantly however Landhuis and Terwellen were able to show that pheromones and anonymous local navigation are not sufficient to avoid positive feedback loops. They therefore conceived their pheromone to include a direction and destination factor, on the basis that the set of active robots were not necessarily following the same trail and that pheromone deposit on corridor corners could otherwise be misleading. Equally it may be asserted that a functioning local navigation system should have noticed the robot was running around in circles and judicious placement of RFID tags, or some clever tag manipulation, may have helped alleviate the need for the direction component. The pheromone itself was represented by the obligatory time-degrading signed integer representing concentration and thus represents the closest attempt so far to emulate a natural pheromone.

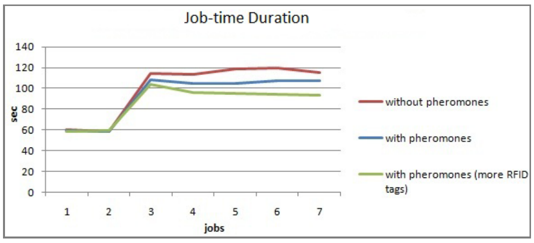

Figure 2: Response times to a blockage (Job 3) given random walk (red) or pheromones (gblue) or increased density of RFID tags (green).

4.3 Results Analysis

It's difficult to conceive of search and rescue operations using tens hundreds of microbots as a viable use-case let alone one requiring pheromones. A trail finding application in a known environment where short term obstacles can occur – hospitals, manufacturing plants, warehouses etc spring readily to mind – does sound like a viable use case and can be shown to have some merit.

Landhuis and Terwellen show that it is possible – given adherence to a fundamentalist view of pheromones – to create a viable application for the industrial arena that functions whilst retaining their essential characteristics – which is, or should be, the reason their emulation was chosen for an application in the first place. In contrast Payton's, and others, rather lackadaisical interpretation of communication theory in general and pheromones in particular, serves only to mask the potential this communication methodology possesses.

5 CONCLUSIONS

Even more dangerous by far is the ad-hock modification or invention of further pheromone properties which serves in practice to get something to work but in fact only serves to mask conceptual failings in the implementation of the research work. The first failing is not to realise that it has not been proven that a bio-property can be abstracted out of its natural eco-system and transplanted into some arbitrary technical solution. The refusal to consider or acknowledge this failure results in implementations of bio-inspired properties are condemned to endless research cycles of abstracted refinement, usually totally ignoring the fact that this particular property resulted from generations of *embodied* refinement in the first place. In short there exists a serious methodological issue with which much of research is conducted in this area which, whilst touched on by previous literature (Pfeiffer 1999), needs to be better acknowledged in future.

Current natural science understanding of pheromones tends to categorise them by the behaviours they trigger. Current technical understanding categorises them under communication methods. The two don't fit. The triggering of a behavioural pattern is deeply connected with the control architecture of the robot, itself a subject where the jury is still in consideration (Gershenson, 2005). Whilst researchers using close-to-life pheromones (gas, light) implicitly acknowledge this through the limitations their medium imposes on them others don't and therefore spend research time chasing issues that would have been better avoided by an appreciation of this inter-connectivity.

There appears to be an unfortunate element of chance regarding the technicalisation of bio-inspired properties. From a methodological point of view a behaviour was specified and a bio-inspired tool was found, it could equally have been that Landhuis and Terwellen remained ignorant of the existence of the Pharaohs ant and hence could have invented some message passing system that functioned more or less as well, in their case the increased robustness of the bio-inspiredness of the solution has not been proven but its relative simplicity certainly has.

Therefore it might be worth investigating the creation of a list of biological behavioural patterns so that technical researchers can better visualise what kind of beast they wish to emulate and more importantly what kind of sensor and actuators are required. There is of course a sizeable ethical dimension to building one's own beast out of a collection of behaviours like some modern day Dr. Frankenstein and, given that scientific method seeks to establish boundary conditions and work inwards to the solution core, a new methodology must be established to ensure that the behavioural patterns do not express themselves all too negatively given some hitherto unknown and unfortunate set of input values.

In conclusion we would like to see a better theoretical appreciation or possibly formal definition of pheromones possibly based on the general rules asserted earlier in the paper on which technical researcher can base their work on and so better understand their advantages and disadvantages.

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