Virtual Pheromones and Neural Networks Based Wheeled Mobile Robot Control

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Abstract: - This paper presents a novel approach on the implementation of the concept of "virtual pheromones" for use in controlling autonomous mobile robots. Rather than being deployed in the environment, the virtual pheromones are stored in a map of the environment maintained and updated by a "pheromone server". This map acts like a shared memory for all the agents, by means of a radio communication link between each agent and the pheromone server. No direct communication between agents is required. The pheromone server can be implemented on a regular computer, a handheld device, or an embedded controller carried by a leader robot. The technique described is equally applicable for guiding individual robots and robot swarms. The experiments show that this method allows significant simplification and cost reduction of the autonomous agents. Several possible applications are discussed.

Key-Words: - Virtual pheromones, mobile robots, fuzzy controller, stigmergy, neural network.

1 Introduction

Since 1959 when Karlson and Lüscher ([1]) discovered and described the natural pheromones, and Grassé ([2]) defined the stigmergy, it took almost 30 years until Deneubourg, Aron et. al. ([3], [4]) noticed the possibility of creating artificial biomimetic agents that communicate and interact with each other by means of a similar mechanism.

In 1989 Beni and Wang ([5]) introduced the concept of swarm intelligence, and between 1996 and 1999, Dorigo, Bonabeau et al. published several works ([6], [7], [8]) exploring the mechanism of self-organization in swarms, and called "ant colony optimization" (ACO) the process that allows foraging ants to find the shortest path between nest and food sources. Afterwards, a great number of scientific papers propose various methods for creating artificial pheromones. Some researchers propose solutions based on spreading chemicals in the environment, just like ants do. ([9], [10]). Others ([11]) use short-range infrared transceivers to relay messages between mobile robots, while others ([12], [13]) propose the use of RFID tags, deployed in the environment, to store some data structures, interpreted as digital pheromones.

The term"virtual pheromone" was mainly used in connection with software agents ([14]).

In the experiment described here, virtual pheromones are embedded in a map of the environment, located in the memory of a remote computer, called pheromone server.

Robotic agents use their own odometric system to periodically report their position to the pheromone server, via a radio communication link. When the pheromone server receives a data packet containing the current position of a robot, it locates the robot on the internal map, then computes the pheromone concentrations for that particular position, and sends back to the client a response packet containing this data. Thereafter, the robot acts as if it had its own differential pheromone sensors, and adjusts its position so that it gets as close as possible to the pheromone trail.

The system can operate with fixed, predefined paths embedded in the pheromone map, or, when multiple robots are involved, it can modify the pheromone concentrations as if the robots would leave pheromone trails on their way, just like real insects do. In this last case, the pheromone paths stored by the server dynamically change as robots move through the environment, creating a realistic emulation of a natural swarm.

This paper is structured as follows:

Section 2 briefly defines the main characteristics of natural and artificial pheromones, and describes how they work.

Section 3 contains the description of the experimental setup, and details of the actual implementation.

Section 4 presents some experimental results, and

Section 5 is reserved for conclusions and future possible research work.

2 Natural Pheromones and Artificial Pheromones

Natural pheromones are chemical substances released in the environment by some insects and other animals, in order to influence the behavior, and sometimes even the physiology of other members of the same species.

Ant foraging is the most common example of pheromone-based interaction. When an ant finds a food source, it starts spreading pheromone on its way back to the nest, leaving a trail that indicates the path to the food to the other ants. Every ant that senses the pheromone trail tends to follow the existing path and reinforces the pheromone trail by spreading additional pheromone.

On the other hand, the pheromone is subject to evaporation, and, when the food source is exhausted, in the absence of reinforcement, the trail disappears. This indirect coordination between agents by means of modifying the environment by an action, which stimulates similar subsequent actions, in a positive feedback process, is called stigmergy (Grassé [2]).

Any model of the natural pheromones should address at least the following aspects:

Pheromone diffusion gradients provide valuable navigational information and also encode useful information about obstacles that obstruct pheromone propagation. Normally, insects sense the pheromone by means of two movable antennas located on the sides of the head. This allows the insect to sense the spatial gradients of the distribution of the pheromone, as resulted from the superposition of the effects of multiple pheromone sources. Figure 1 illustrates this mechanism.

Pheromones evaporate over time. This process reduces obsolete or irrelevant information, and also provides the colony with a mechanism to find the shortest path to the food.

If two or more paths of different lengths are available between the nest and the food source, longer paths require more time for the ants to reach their target. The process of evaporation reduces the overall intensity of the pheromone on longer paths, and therefore more ants tend to choose the shorter path. Eventually, the shortest path is used by most of the ants, and longer paths disappear. See figure 2 for an illustration of this process, as explained in the so-called double bridge experiment ([4]).

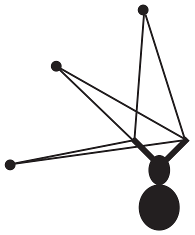


Fig. 1. Differentially sensing the pheromone gradients.

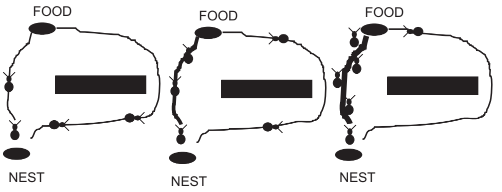


Fig. 2. An illustration of the double bridge experiment

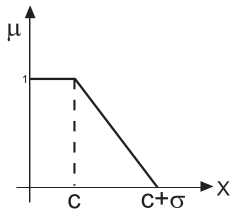


Fig. 3. Pheromone intensity as function of the distance

To describe the spatial distribution of the pheromones, we have used Z-shape functions, defined by (1):

$$\mu(x) = \begin{cases} 1 & x \in [0 \quad c] \\ 1 - \dfrac{|x-c|}{\sigma} & x \in (c \quad c+\sigma] \\ 0 & x > c+\sigma \end{cases} \tag{1}$$

This function defines the variation law of the intensity of pheromone sensed at the distance x from the source. The shape of the function (1) is presented in figure 3.

The variation of the pheromone intensity with the time can be modelled as a counter C_i, which is incremented or decremented at discrete time moments T_i, as in (2):

$$C_{n+1} = C_n + Qf(T_{n+1} - T_n) \tag{2}$$

where:

$$f(t) = \begin{cases} 1 & t < \tau \\ 1 - int\left(\dfrac{T_{n+1} - T_n}{\tau}\right) & t > \tau \end{cases} \tag{3}$$

Q is a positive constant, representing the quantum of reinforcement/evaporation of the pheromone, $int(x)$ is the integer part of x, and τ is the evaporation time constant.

For N sources of pheromone, the resulting pheromone intensity is, for each point:

$$P = \sum_{i=1}^{N} C_{n+1}(t)\mu(d_i) \tag{4}$$

where d_i are the distances from the considered point to each of the pheromone sources. The equation (4) is the model of the virtual pheromone.

3 Description of the Experiment

- The Idea

Consider an autonomous mobile robot, with two independent drive wheels, and an additional caster wheel, having the kinematic variables as shown in figure 4.

The robot has its own odometric system, and an on-board embedded microcontroller is able to read the position information and to send it over a radio communication link, according to a specific protocol.

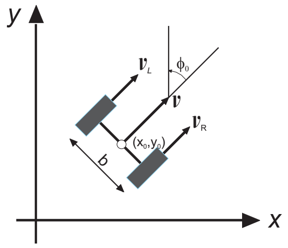


Fig. 4. Kinematic variables of the robot

The embedded control unit is also able to generate set-point values for υ_R and υ_L. See figure 5, for an overview of the equipment located on the robot.

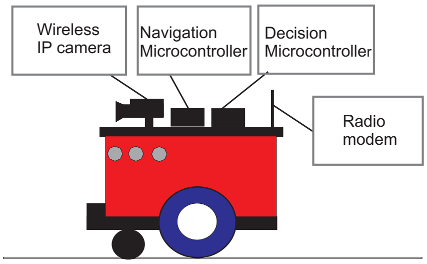


Fig. 5.The equipment located on the robot

Fig. 6. Mobile platform Pioneer 3-DX WMR.

The on-board controller communicates through a radio modem with a "pheromone server", embodied as a computer running a dedicated software application, located anywhere on the ground,within the radio visibility range (see figure 6).

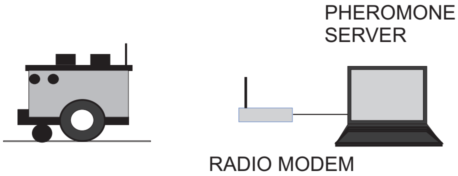


Fig. 7. The experimental setup

The pheromone server stores a map of the environment, containing an arbitrary number of cells, as shown in figure 7.

It is assumed that the internal map of the environment, stored by the pheromone server, and the odometric systems of all the robots have the same origin of the system of coordinates. The pheromone map acts like a shared memory area for all the agents.
Note that the pheromone information is embedded in the environment map, as positive numbers assigned to the nodes defined by the intersection of the boundary lines of the cells (dark points in figure 7 indicate the presence of pheromone sources).

The robot sends "pheromone information requests (PIR)", as data packets containing its current position (x_0, y_0, ϕ_0), as reported by the odometric system.

Upon reception of a PIR, the server locates the point (x_0, y_0, ϕ_0) on its own internal map, then computes the position of the "pheromone sensing antennas" (x_L, y_L) (x_R, y_R) with (5) (see figure 8).

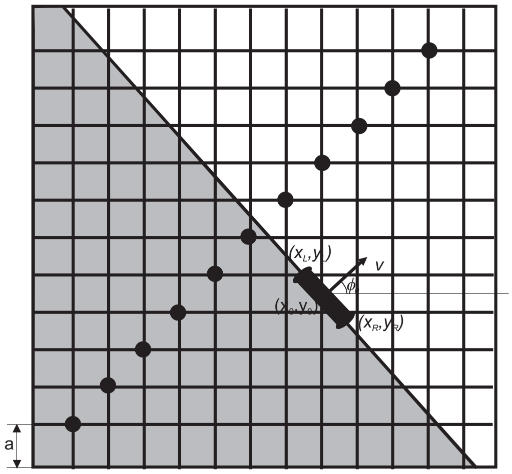


Fig. 8. The map of the environment as represented by the pheromone server

$$\begin{aligned} x_R &= x_0 - \frac{b}{2} sin\,\phi_0 \\ y_R &= y_0 - \frac{b}{2} cos\,\phi_0 \\ x_L &= x_0 + \frac{b}{2} sin\,\phi_0 \\ y_L &= y_0 + \frac{b}{2} cos\,\phi_0 \end{aligned} \tag{5}$$

where b is the “bias” of the robot, defines as the distance between the planes of the drive wheels (see figure 4).

Then, the server computes with (4) the values P_L, P_R of the intensities of the pheromone, corresponding to the points $(x_L, y_L)\,(x_R, y_R)$, and sends these values back to the robot.

Note that, in our experiment we assumed that the sensitivity to pheromone is directional, so that the gray area in figure 8 is “invisible” when computing P_L and P_R.

Having P_L and P_R, a simple inference engine, at the level of the embedded navigation controller, located on the robot, can compute the values υ_R and υ_L to correct the position of the robot for bringing it closer to the pheromone path (see for example [12] and [15] for an example of implementation of a fuzzy controller to this purpose).

For this experiment, we have used (6) to compute the values of the speeds for each drive wheel:

$$\begin{aligned} \upsilon_L &= \begin{cases} K\left(1-\left|P_L-P_R\right|\right) & P_L > P_R \\ K\left|P_L-P_R\right| & P_L \le P_R \end{cases} \\ \upsilon_R &= \begin{cases} K\left|P_L-P_R\right| & P_L \ge P_R \\ K\left(1-\left|P_L-P_R\right|\right) & P_L < P_R \end{cases} \end{aligned} \tag{6}$$

assuming that $P_R, P_L \in [0 \quad 1]$ and K is a scaling constant.

Note that the whole process of computing the speeds υ_R and υ_L, starting from a given distribution of pheromones across the environment can be represented as a neural network (see figure 9).

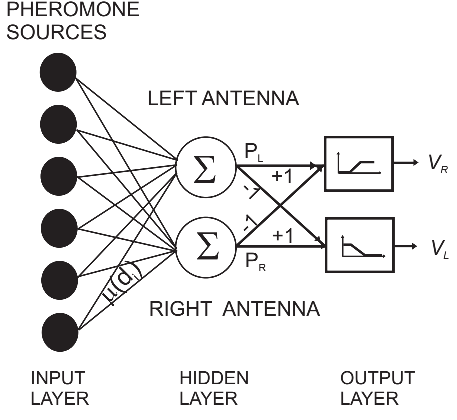


Fig. 9. The equivalent neural network describing the process

In this structure, the neurones of the input layer are the discrete pheromone sources, and therefore weights of the synapses between the input layer and the hidden layer are determined only by the concentrations and spatial distribution of the pheromone sources.

We called this type of pheromone-mediated synapses “exo-synapses”.

Since the weights of the synapses between the hidden layer and the output layer are fixed (+1, -1), and the weights of the exo-synapses are determined by external conditions, this network does not need training. The “intelligence” of each mobile agent is determined only by the swarm that generates the particular pheromone distribution.

- Notes on the Communication Protocol

Any reliable and fast wireless communication protocol is suitable for the communication between mobile agents and the pheromone server. We have used low-cost radio modems, with half duplex communication in the ISM band.

Only one network peer is allowed to use the communication medium at any given time, otherwise a data collision occurs. Therefore, the protocol implemented must obey the rule “listen before you talk”.

Other requirements considered for designing the protocol were:

The protocol must allow communication between the pheromone server and as many client agents as possible.

The protocol must allow the use of multiple types of pheromones within the same network.

The protocol must provide a reliable error detection to avoid incorrect decisions caused by communication errors.

The general structure of the messages is inspired by the industrial protocol DF1 (defined in ANSI X3.28 subparagraphs D1 and F1), and is presented in figure 10.

MESSAGE STRUCTURE

START OF MSG	CLIENT ID	OPCODE	DATA	CRC	END OF MSG

CLIENT REQUEST

START OF MSG	CLIENT ID	OPCODE	X_0	Y_0	ϕ_0	CRC	END OF MSG

SERVER RESPONSE

START OF MSG	CLIENT ID	OPCODE	P_L	P_R	CRC	END OF MSG

Fig. 10. Detailed structure of the protocol messages

The START OF MESSAGE, and END OF MESSAGE fields are two-byte sequences (DLE-STX, and DLE-ETX respectively) aimed to clearly define the boundaries of the messages. This allows variable length data fields. If a START OF MESSAGE sequence has been detected, all clients must wait for the end of message, plus a random time delay, before attempting to access the communication channel.

If a DLE byte (0x10) occurs in the body of the message (i.e. any of the fields CLIENT ID, OPCODE, DATA, CRC), this must be transmitted as two DLE (0x10, 0x10). This mechanism is called DLE stuffing, and is intended to provide a means for avoiding false detection of message delimiters. The stuffed DLEs must be removed by the receiver.

The one-byte field CLIENT ID identifies the transmitter in messages sent by clients, and the destination in messages sent by the server. All the clients receive and interpret all the incoming messages, but only the received messages whose CLIENT ID field match the predefined, hardwired ID are used.

The field OPCODE (one byte) allows the definition of multiple types of pheromones, as well as additional commands like “pick a load”, “drop the load”, etc. This field is also used to distinguish between messages generated by clients, and those generated by the server.

The length and structure of the DATA field is variable, depending on the OPCODE.

The field CRC (Cyclic Redundancy Check) is a 16-bit polynomial checksum for error detection, and data collision detection. Stuffed DLEs are not considered in the CRC calculation.

Note that the messages do not contain a time-stamp. This eliminates the need for the clients to have a synchronized real-time clock. The evaluation of the process of pheromone evaporation is conducted by the server.

4 Experimental Results

- Objectives

The objectives of the experiment were:

Demonstrate the feasibility of the idea

Compare the performances of the virtual pheromones based controller with another controller (namely, the fuzzy controller described in [15]) for path following.

Evaluate the influence of the various parameters of the pheromone model.

General Conditions

The experiment was designed to work with the wheeled mobile robot Pioneer3-DX manufactured by MobileRobots Inc. (16]).

During the simulation phase of the experiment, we have used the robot simulator MobileSim, offered by MobileRobots Inc., specifically designed for the Pioneer 3-DX WMR robot. The pheromone server was later tested with real robots, and produced identical results.

The pheromone server was implemented as a dedicated software application, running on a regular desktop computer.

At the client side, a simple embedded microcontroller device was used to implement the communication protocol, and to generate motion commands to the robot.

The communication speed was set to 9600 baud, limited by the performances of the radio modems.

A time-invariant, predefined distribution of pheromone was used to define a virtual path to be followed by the robots. The evaporation process was not explored so far.

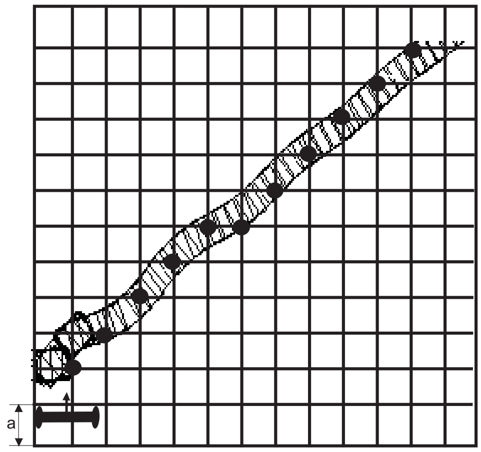
Only one robot was used in this experiment.

The environment is assumed to be a horizontal plane surface, with no obstacles.

To evaluate the performance of the algorithm, we have recorded the successive positions of the mobile robot for 10 seconds, at 0.2 seconds intervals. The average position error, defined as the distance between the target path and the actual measured position, was used as evaluation criterion.

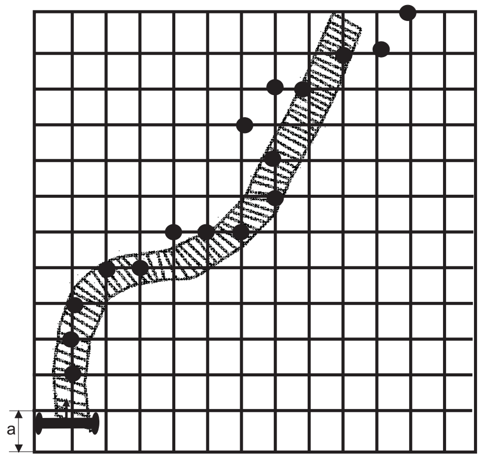
- Results

Figures 11 and 12 present the Pioneer 3-DX path, as recorded by MobileSim, superposed with the target pheromone map for two different pheromone distributions.



a=200mm, b=380mm, σ=300mm

Fig. 11. Recorded path vs. pheromone distribution



a=200mm, b=380mm, σ=600mm

Fig. 12. Recorded path vs. pheromone distribution

In principle, the size of the map cell ‘a’, can be arbitrarily selected. Smaller values of ‘a’ allow better approximations of any curve, but the computational load of the server is proportional with N^2, where N is the total number of cells per map axis.

For larger values of the pheromone diffusion factor σ, the behavior of the system is illustrated in figure 12.

The overall performance of the system for path following can be tuned to levels entirely comparable to those of a fuzzy controller, but pheromone based solution is simpler and much more flexible.

5 Conclusions

The main drawback of the proposed solution derives from the fact that it relies on the odometric system of the mobile vehicle, which is often imprecise, and subject to cumulative errors. For outdoor applications, the use of GPS or DGPS locators might give better results.

The main advantage is that it makes the task of path-following as simple as instructing a toy-robot to follow a line painted on the floor.

Further research is required in the following directions:

Study the effect of pheromone evaporation with multiple robots.

Experiment with maps containing obstacles.

Experiment with repellent pheromones.

Experiment with GPS locators.

Examine the possibility of using ant colony optimization algorithms for finding the best path to a specified goal point.

The neural network perspective on swarm intelligence might be useful in robotics and biology.

Identify other possible applications beyond the obvious military applications, e.g. for guiding intelligent wheelchairs in supermarkets or other public spaces, etc.

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