# The Pheromone of Ant Emulated by Petri Net Inserted Inversely in RFID Database for Swarm Robots

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Abstract. Swarm robotics has several challenge options to provide control management of social behavior to achieve specific goals. Bio-inspired approaches are on the top of the solutions that do not use artificial intelligence, - specially versions based on ant colony algorithms - where local information spread in the application environment is used instead of local centralized database. Such approach is specially suited to applications in digital manufacturing because of the high flexibility of this production environment. In this work is presented an alternative proposal that emulates pheromone trough RFID tags spread in the manufacturing environment with enhanced memory capacity. Advances in cost and complexity of this implementation would come out from an integrated system were robots emulate an ant colony which use pheromone represented by Petri net inserted inversely in an RFID distributed database called iPNRD. In the iPNRD approach, the environment receives only RFID tags, which stores a PN trigger vector, while the robots have a RFID reader, which provides their own PN incidence matrix and marking. During tag data capture the robot updates its marking vector. This article will show how iPNRD emulates the pheromone of ants, assuming the environment possesses embedded readers. To avoid robots' collision, the iPNRD solution assist two red/green semaphores: one in the feed source and another in pheromone area. That solution has lower complexity and the implementation has a relative low cost. The interaction between robots and environment and the resulting behavior are also modeled using Unified Extended Petri Nets where pseudo-boxes are used to represent the flow of communication concerning robots and environment.

Keywords: Swarm robots  $\cdot$  pheromone of ant  $\cdot$  iPNRD  $\cdot$  RFID  $\cdot$  Petri Net.

#### 1 Introduction

The fundamental problem in cooperative robotics is the coordination of multirobots in dynamics environment [1] once coordination normally implies synchro-

nizing robot's actions and exchanging information among them. A bio-inspired approach is suitable to model this information exchange either based on centralized or distributed architectures. Petri Nets (PN) have been applied in this context [2,3].

The behavior of an ant colony and the interactions of robots in a swarm are both based on behavioral rules that only exploits local information [4]. Therefore, the decisions on a swarm must be defined by local interactions using pheromone. Originally, the pheromone flow of information is based in the synthesis of a chemical substance by a living being (an ant for instance) that causes a specific reaction in a receiving individual of the same specie [5]. This reaction can be a behavior modification or a determination of physiologic state.

There are different ways to represent the pheromone, each one with its peculiarities. [6] developed a heating trail based on a 70W lamp and a pyroelectric sensor. One problem is that the electrical generation of heat is not possible, even in bigger mobile robots, because of constrains in battery power. [7] applied ethanol and alcohol sensor to emulate the ant pheromone. Although this is a very realistic imitation of the pheromone-based trails of ants, the chemical sensors used in this setup and the combination of robotics and substances have been shown to be very unreliable and not very practical. [8] presented an approach which emits ultraviolet light onto phosphorescent ink, but collision avoidance between robots is not reliable. [9] showed a digital pheromone via the interaction between agents and radio frequency identification (RFID) tags. Each robot receives two RFID readers and identify the original pheromone sources insider RFID tags. The pheromone calculus is centralized inside the mobile robot. Therefore, thus the ant pheromone in swarm mobile robots requires collision avoidance, battery power constrains, practical implementation and independency between the environment pheromone and mobile robots.

Since the initial RFID application with the Walmart, in early 2000's, much attention has been pointed out to this technology. Current RFID market still shows a lot of optimism and maybe overestimation in the success of this technology. However, RFID implementation is below its potential because of the lack of process information embedded together with automatic data gathering and process [10]. Indeed a RFID system also can be used as an internal position system (RFID IPS) [11]

Another application of RFID systems is in manufacturing and logistic process where a Petri Net can model the product behavior. Elementary Petri Net stored in RFID database (PNRD) [12] provides a formal data structure to tagged objects, which defines and introduces the process activity into a RFID disperse database. In this way, the tag stores a Petri net (incident matrix and object actual state), and readers have the control (marking) vector associated with the reading activity and a conditioning sentence allowing the calculation of the The tag updates its own state vector after the calculation.

Since each tag refers to a single object, the PNRD must be a safe Petri net, and the calculation of the next state must be a unimodular vector. There are also some variants of PNRD: i) he PNRD extended to distance integrates PNRD with

RFID IPS to control mobile robots [10]; ii) the inverted PNRD (iPNRD) changes what kind of information each RFID component stores, that is, the tag stores the control vector and additional historical data and readers have the incident matrix and object current state [13]. The PNRD and variants approaches are able to work offline and are able to determinate whether a process has been reaching desirable state. Figure 1 presents Petri net and RFID integration through PNRD or iPNRD. In both Petri net is able to model, control, deals with concurrency, and provide several formal properties to support verification such as model checking and invariant analysis. The RFID tag support automatic data capture returning a unique identification, and can work as a position sensor. It is possible to read up to 1000 tags per second, depending on RFID frequency. Whereas RFID can be a dynamic distributed database is pointed out as a smart product cornerstone. PNRD and iPNRD are Petri net and RFID intermediate, it means, as PNRD is a formal data structure based on Petri net, it is able to distribute Petri net components in order to update automatically Petri net state and to identify in real time process exception in a net-work independent manner.

Figure 1 presents Petri net and RFID integration through PNRD or iPNRD. On one hand Petri net can model, control, deals with concurrency, process and it has several formal properties as model checking and invariant analysis. RFID, on the other hand is an automatic data capture tools with a unique identification, and it can become a position sensor. It is possible to read up to 1000 tags per second, depending on RFID frequency. Whereas RFID can be a dynamic database it is pointed out as a smart product cornerstone [11]. PNRD and iP-NRD are Petri net and RFID intermediate, it means, as PNRD is a formal data structure based on Petri net, it can distribute Petri net components onto RFID components in a distributed logic approach. The PN formal structure allows the automatically state update, and the real-time process exception discovery.

This paper aims to bring up how Petri net (PN) and RFID can be integrated to emulate ant pheromone applied to robot swarms. To achieve this goal, it is necessary to reach the requirements related to the ant pheromone in swarm mobile robots, so the need of smarter environment is mandatory.

In the next section additional related works on swarm robotics are presented and the iPNRD is presented in section 3. The fourth section shows the system proposal. Lastly, section 5 presents conclusions, followed by the acknowledgement and the references.

### 2 Related works in swarm robots and ant pheromone

One of the great challenges related to the swarm of robots lies in the control algorithm and in the strategies of cooperation between them, without any collision. There is a search for new models of behavior and innovations/enlargements to those already studied.

According to [9], passive RFID tags spread out onto the floor can be used as storage of the field information and the agents communicate with other agents by updating a pheromone trail through the tags. In this approach the robot



Fig. 1. Petri Net and RFID interactions.

stores information in the tags but this information is static and only the robot manipulates it. In this paper the pheromone is logically independent of the robot although the robot processes all pheromone calculus.

[14] treated the autonomous exploration of unknown environments with one or multiple robots. The proposal was to evaluate robots' ability to avoid obstacle (labyrinth's wall) and to avoid paths already covered by other robots. For this 18 laser distance sensors were installed to each robot to map the environment. [15] simulated such a problem of robot displacement such that when an obstacle was perceived a potential rotational field was applied to avoid collision between the robots and the obstacle.

In relation to the ant pheromone, RFID tags arranged in the environment can works as pheromone carriers [16], and the pheromone map can be used to guide robots' motion without any localization system. In addition, the inverted pheromone [17] works as a repulsive force between robots. In this scenario, the inverted pheromone is used to spread the robots in the environment.

# 3 iPNRD

According to [10] the PNRD is a RFID data structure based on the elementary Petri Net formalism or Low-Level Petri Net (LLPN) and it can be described as a five-tuple (P, T, A, w, M0). As PNRD has a 1:1 relation with each tag, and PNRD must be a safe Petri net with at most one token in each place. In this approach each tag stores its own incidence matrix and state vector of a Petri net referring to the process part to which the tagged object in question participates; and each reader stores the corresponding control vector list and the triggering conditions. The PNRD operation is based on the capture of the tagId followed by the  $A^T$  or incidence matrix, and the tag state vector  $M_K$ . The software responsible for calculating the next state finds the corresponding  $u_K$ (control vector) related to the conditioning set composed by tagId, tag state, antennaId, readerId, and other optional additional data, such as time interval, the distance among other. The calculation of the next tag state  $M_{K+1}$  follows Eq. 1.

$$M_{K+1} = M_K + A^T . u_K, k = 1..n$$
(1)

The next tag state result must be evaluated. If the result is a unitary vector, this means that the Petri net remains elementary and safe, which is consistent with the fact that each tag has a 1: 1 relation with Petri Nets. This result is supposed in agreement with the expected process flow, allowing the record of the  $M_{K+1}$  in the tag memory as new tag state. Otherwise, the Petri net is no longer safe, indicating an abnormality in the expected follow-up of the process, which can generate a real-time warning signal. It can monitor the process of each tag individually. Even flexible processes can be stored, giving to the tagged object the ability to follow different paths if properly planned and modeled previously. One of the possible problems during the execution is the appearance of conflicts. Conflicts occur when the same antenna/reader is associated with more than one transition relative to the same tagId, tag state, and additional data. A decision algorithm can be applied to choose what transition should be triggered to solve the conflict. Hence, PNRD is based on a previously modeled system, and it can check whether the desirable model is followed or not. [10] present a PNRD didactic example.

[13] show iPNRD approach as PNRD which each tag stores the control vector and additional historical data and readers have the incident matrix and object actual state; and it is applied on outlander search and rescue robots. It's important to highlight that the PNRD and iPNRD are the Petri net data structure on RFID elements, that is, the insertion of places, arcs, transitions and marking into readers and RFID tags.

It is possible to point out that in both approaches there are a strong connection between RFID and Petri Net, which reduces the need for queries in external databases although there is a need to predefine the PN process in advance. After this process modeling, an operational management system must attribute a specific PN process and part (incident matrix, state vector or trigger vector) to each tagged object and RFID reader.

To summarize theses definitions, Tab. 1 presents the original PNRD and iPNRD approaches with its variants. There are three different ways to distribute Petri net elements between RFID reader and tag. This paper uses the original iPNRD where the robot carries the RFID reader and the environment has the passive tag.

Formalism		Reader	Tag
	Original	$u_K$	$M_K$ and $A^T$
PNRD	Variant 1	$A^T$	$M_K$ and $u_K$
	Variant 2	$M_K$	$A^T$ and $u_K$
	Original	$M_K$ and $A^T$	$u_K$
iPNRD	Variant 1	$M_K$ and $u_K$	$A^T$
	Variant 2	$A^T$ and $u_K$	$M_K$

 Table 1. Comparison between PNRD and iPNRD showing where each Petri net element is stored.

The approach of this work is the environment (world) with passive RFID tags strategically spread in it and mobile robots have a RFID reader that reads tag data when it passes through the tag, the tag information can change mobile robots' behavior, and the mobile robots can write new information inside the tag. In this paper, tags represent the pheromone of ants, the energy source, and semaphores to avoid collision during pheromone data capture. The iPNRD is applied in this scenario, so the robots carry the incidence matrix and its own marking while the tag carries the trigger vector. Since the ants (robots) are homogeneous, the robots modeling and characteristics are the same for every robot.

#### 4 System proposal

The system's bench (see Fig. 2) is based on [4] where there are two trails between the source and the nest: trail A (shorter path) and trail B (longer path). It's expected that over time the robots choose the shorter trail and for this to be possible, the pheromone tag must receive information from the robots and inform the best trail. The source tag simulates an energy source and the robot consumes energy stored in the tag to return to the nest.

The robot moves in the bench following the Petri net presented in Fig. 3. It can be noticed that each tag, spread in the environment, is considered as a mobile robot transition and each place defines a set of actions that the mobile robot must execute, such as place p2 (*Robot waits green light*). In this specific place the robot must stop on the tag, write its presence inside the tag, wait for the environment reader to change the semaphore color from red to green, then continuous to move to the next tag. As well as for the place p2 all places in the mobile robots' PN are considered as macro places where each place has a set of specific actions.

The transition pheromone tag, on the other hand, stores the more attractive trail, following the ant pheromone algorithm which are going to be presented in 4.1 subsection, defining the trail to be followed.

This mobile robots' PN could be defined as finite automata, or as finite state machine, or as sequential function chart (Grafcet), but since environmental and pheromone modeling uses Petri Net the authors decided to standardize the



Fig. 2. Proposal bench based on [4]

modeling. Also, as shown, the places modeled for the mobile robots indicate that the actions of the robots, while the transitions are represented by the capture of the tags. Thus, iPNRD can be applied to this case.



Fig. 3. Mobile robots' PN.

Table 2 presents the Mobile robots' PN places and transitions. Places p4 to p9 (robot following trail A) are quite like places p10 to p15 (robot following trail B) and the difference between them is the movement that the robots make and the tag (transition) it achieves. For example, p4 is the place where the robot moves

from pheromone area to source area following trail A. The tag S1 (transition t4) indicates that the robot achieved the source area. Looking for trail B the respective place and transition for the same situation are p10 and t11 (tag S2).

Table 2. Mobile robots' PN places and transitions.

places		trar	transitions		
p1	Robot moves in nest	t1	Tag N1		
p2	Robot waits for green light	t2	Pheromone Tag		
p3	Robot reads pheromone	t3	Tag N5		
p4	Robot leaves semaphore 2 from A	t4	Tag S1		
p5	Robot waits for green light from A	t5	Source tag from A		
p6	Robot reads source from A	t6	Tag S3		
p7	Robot leaves semaphore 1 from A	t7	Tag N2		
$\mathbf{p8}$	Robot waits for green light from A	t8	Pheromone tag from A		
p9	Robot leaves semaphore 2 from A	t9	Tag N4 from A		
p10	Robot leaves semaphore 2 from B	t10	Tag N6		
p11	Robot waits for green light from B	t11	Tag S2		
p12	Robot reads source from B	t12	Source tag from B		
p13	Robot leaves semaphore 1 from B	t13	Tag S4		
p14	Robot waits for green light from B	t14	Tag N3		
p15	Robot leaves semaphore 2 from B	t15	Pheromone tag from B		
		t16	Tag N4 from B		

It is possible to verify that if the mobile robot reads the tag N5, it means that the pheromone calculus chose trail A. Otherwise, the mobile robot is going to read the tag N6. During the source capture, another semaphore related with S1 and S2 tags works similarly to the nest one. After the source capture, the mobile robot returns to the nest semaphore (N2 and N3 tags), it stores information to next pheromone calculus and it enters in the nest when read N4 tag.

Three important points must to be considered:

- How to avoid collision between the robots;
- How to synchronize the robot and the environment readers to read and write the same tag and;
- How to define the direction to be taken from the robot to the source.

To avoid collision the robots are going to follow a line tracking with sensors and it must sense walls around itself. In each path there are two lines, so the robot moves to the source in one line and returns to the nest in another one. When the robot moves along trail A, it follows from the nest to a source close to the outer wall and returns close to the inner wall, while at trail B is the opposite. In the nest there is no collision between the robots as it follows a unique path in the counterclockwise direction forming a FIFO (First In, First Out) queue.

Even so, there are two points of concurrency that is necessary to be aware, it means, during the reading of the source tag and the pheromone one. The source tag can be reached from trail A and trail B, and the pheromone tag can be reached when the robot wants to leave the nest and when it wants to return from both trails. To avoid collision in these cases, there are two red/green semaphores, which is detailed in section 4.2.

#### 4.1 Pheromone of ant

Pheromone function as chemical messengers among individuals [5]. In this paper, the pheromone is emulated by iPNRD based on the interaction of environment and mobile robots. A passive RFID tag stores information that the robot uses to determinate its behavior, and the environment can change the RFID tag information as required.

As mobile robot and the environment can change the tag's information, there is a concurrency in communication if the robot RFID reader and the environment RFID reader try to write or read the tag at the same time. Figure 4 presents an example of RFID reading collision between the mobile robot and the environment in the pheromone tag. There is a need of synchronization between the robot RFID reader and the world RFID reader. This synchronization can be implemented applying a time lag between the mobile robot clock the environment clock. These clocks are activated on the rising edge and deactivated on the falling edge. For this synchronization, the robot clock and the environment's clock are 180 degrees out of phase.



Fig. 4. RFID reading collision in the pheromone tag.

Since the pheromone is a volatile substance and its concentration decreases in time, the world can decrease pheromone value according to Eq. 2, where c\_value is the concentration value stored on the tag. This equation is proposed because the pheromone value decreases inversely proportional to the concentration. Low concentration takes lesser time to evaporate than high concentration.

$$Pheromone = c_{value} \cdot e^{\frac{-t}{c_{value}^2}}$$
(2)

Figure 5 shows how the pheromone tag is going to work over time. Every time a robot comes back from source tag, it increases the pheromone concentration stored at pheromone tag with the power removed from the source. The world's reader decreases the pheromone concentration according to the Eq. 2, and every time the pheromone tag is updated by the robot, the world's reader starts the equation from t = 0. This function is applied to both trails, and the environmental reader stores the comparison of them to assist the mobile robot trail definition.

According to the amount of pheromone in each track a specific value will be saved in the pheromone tag (00, 01 or 10). It is observed that until the time T1 the amount of pheromone in the two trails are identical since no robot has returned to the nest with food. In this case the value saved in the tag is 00 and when a robot reads this information it decides at random which path to follow. In the present case, a mobile robot has returned to trail A with which the value of the pheromone concentration has increased and until the instant T2 this value is higher than the pheromone concentration in the trail B, so the value saved in the tag is 10 indicates that the robot must take this path when leaving the nest. From T2 to T3 the saved value is 01 and indicates that the mobile robot must follow the path B. From T3 to T4 the concentration of pheromone in track A is higher than the concentration of pheromone in track B, then the value saved in the tag is again 10. It is observed that at instants T2, T3 and T4 the amount of pheromone in the two tracks is the same. With this the value saved in the tag is 00 which indicates that the robot can follow any of the paths. In this work when this situation happens the robot chooses to follow at random.

Figure 5 presents 7 robots in the bench over timer. Robot 1 to 4 are arriving the nest and robots 5 to 7 are leaving the nest. When the robot 1 reaches the pheromone tag it stores the information that it came from trail A, so the pheromone concentration in trail A increases, and when robot 6 reads the pheromone tag, it reads the value 01 and moves to source area following trail A. Robots 2 and 3 reaches the pheromone tag and now the trail B has more pheromone concentration. So, when robot 7 leaves the nest, it reads 10 and moves to source area following trail B.

As presented in [18], pseudo-boxes are an observable condition that is not controlled by the modeled system and could stand for control information external to the hierarchical components. Thus, pseudo-boxes must be considered in the structure of the net but should not affect its properties or the rank of the incidence matrix. The pseudo-box is a form of messages' exchange between the agents in the system. Fig. 6 shows the environment RFID reader at the pheromone tag PN, where this reader can perform three different readings (*reads empty*, *reads trail* A and *reads trail* B transitions) or store three distinct information (*stores* 00, *stores* 01, and *stores* 10). The reading occurs periodically (the *reads empty* transition means that no robot stored any new information), and when the robot is returning from the source, the robot stores the information



Fig. 5. How pheromone concentration works over time.

of what path was used (trail A or trail B) generating a pseudo-box (psPhe1 or psPhe2) during the environment RFID reader data capture, depending on the trail. These pseudo-boxes are sent to the pheromone algorithm function, which calculates which trail is the most appropriate. If both trail have no pheromone, the pheromone algorithm function sends 00 as message (psPhe3). If the trail A has more pheromone than trail B the pheromone algorithm function sends the message 01 (psPhe4), otherwise it sends 10 (psPhe5). In case of both trails have the same value of pheromone, the message is 00 (psPhe3). The environment RFID reader at pheromone tag recording occurs when it receives one of this 3 pseudo-boxes (psPhe3 to psPhe5). The Reader ready place has no conflict based on the information it stores or reads on the pheromone RFID tag.

Similarly, the robot RFID reader at the pheromone tag (see Fig. 7) can perform three different readings (trail A; trail B; and without pheromone or same amount on both trails) or store two distinct information (returned by trail A or returned by trail B). Clearly the pheromone RFID tag stores the trigger vector of both RFID readers.

As can be seen, both PN have inhibitor arcs. These arcs mean that storage has priority over reading. [19] has defined how to use a PN with inhibitor arcs as a Logic Petri Net (LPN) and in this work, the inhibitor arcs are treated in the microcontroller code. When the inhibitor arc is able, the transition can not be triggered. So the inhibitor arc is a precondition to the transitions.



Fig. 6. Environment RFID reader at the pheromone RFID tag PN with pseudo-boxes.



Fig. 7. Mobile robot RFID reader the pheromone RFID tag PN with pseudo-box.

#### 4.2 Red/green semaphore

To avoid collision over source and pheromone tags there are two semaphores in this scenario, one in source area and the other one in pheromone area. The robot can reach the source tag from two paths, so the source semaphore avoids robot collisions using four tags. Two of these tags are the red/green semaphores and makes the robot wait (if the source semaphore RFID tag store red as information) or move (if the source semaphore RFID tag holds green as information), and the other two tags just indicates when the robot has left the source area enabling another robot to pass through the sourcing area.

For the pheromone semaphore (semaphore 2) there are three paths (one to leave the nest and two to reach the nest from each trail), so there is a need of six tags. Three of these tags indicates when the robot has left the pheromone area (N4 to N6) and the other three are the red/green semaphores (N1 to N3). Fig. 8 presents how semaphore 2 is implemented physically.



Fig. 8. Semaphore 2 tags.

Table 3 presents the action sequence in the pheromone area during leaving and arriving nest. Both are similar, except during stage 5 when the pheromone is read (for the mobile robot leaving the nest) or the pheromone is stored (for the mobile robot returning from a trail). The mobile robot and environment change information through tag data capture and storage and tags are the media to exchange this information.

Action	Leaving Nest		Arriving Nest				
10000	Robot	Environment	Robot	Environment			
1	When the robot reaches a semaphore N1 tag its stops and stores its presence in the		When the robot reaches a semaphore N2 or N3 tag, its stops and stores its presence in				
2	tag.	When the envi- ronment reads at N1 tag a robot presence, it informs to other semaphore entrance readers (N2 and N3 tag) and if the semaphore is free, it changes its color to green	the tag.	When the envi- ronment reads at N2 or N3 tag a robot presence, it informs to other semaphore entrance read- ers, and if the semaphore is free, it changes its color to green			
3	Reads the green light and moves to the pheromone tag position		Reads the green light and moves to the pheromone tag position				
4		Changes Traffic light to busy, informs other semaphore en- trance readers and changes its color to red		Changes Traffic light to busy, informs other semaphore en- trance readers and changes its color to red			
5	Reaches pheromone RFID tag, reads the trigger vec- tor, and defines what trail to be tracked		Reaches pheromone RFID tag and stores the trail followed.				

Table 3: Mobile robots' PN places and transitions.

Action	Leavin	g Nest				Arrivir	ng Nest		
Action	Robot	Environm	nent		Robo	t	Envi	ronn	nent
6							Reads	$^{\mathrm{the}}$	e in-
		Reads for	new				formed	l	$\operatorname{trail}$
		information	from				and	υ	ipdate
		pheromone					the	phere	omone
							inform	ation	
7	Reaches trail in-			Reach	nes	$\operatorname{trail}$			
	dicator tag (N5 or			indica	$\operatorname{ator}$	$\operatorname{tag}$			
	N6) and stores its			(N4)	and	stores			
	presence.			its pr	esence	э.			
		Reads the	robot				Reads	the	$\operatorname{robot}$
9		presence,	in-				presen	ce,	in-
		forms to	other				forms	to	other
		semaphore	en-				semapl	nore	en-
		trance	read-				$\operatorname{trance}$		read-
		ers (ch	anges				ers	(cł	nanges
		semaphore	to				semapl	nore	to
		free)					free)		

When the mobile robot is leaving the nest, it reaches the semaphore tag N1 (Fig. 9), it stops, and stores it presence in the tag. Next, the environment RFID reader at the N1 RFID tag perceives the robot presence, and it informs other semaphore entrance readers (through Robot Leaving Nest pseudo-box) and if the semaphore is free, it changes the semaphore color to green. After that, the robot reads the green signal and moves to the pheromone tag. The environment sends messages to other semaphore entrance readers indicating that the semaphore is busy and changes the semaphore color to red.

When the robot reaches the pheromone tag, it reads the trigger vector stored at the tag (psPhe3 to psPhe5) which defines what trail must be followed. If psPhe3 is read, it means that the pheromone in trail A has the same weight of the pheromone in trail B, and then the mobile robot controller chooses randomly what trail to follow. The psPhe4 and psPhe5 defines the trail. The robot moves through the tag N5 if the pheromone indicated the trail A or through the tag N6 if the pheromone indicates the trail B. At this point, the robot stores its presence, so the environment reader at the tag N5 or N6 can read this information and inform other pheromone entrance RFID readers that the semaphore is free.

The higher priority is at tag N2, since that tag indicates a robot returning to nest from the shorter trail. The robot leaves the nest (tag N1) has the lowest priority. Note that a token changes between *SemaphoreFree* and *SemaphoreBusy*, so the mobile robot returning from source disable the semaphore and it's kept as red. The semaphore only turns free if a robot pass tags N4, N5 or N6, which means, it has left the pheromone area, and other robot can pass through. The places *GreenN1*, *RedN1* and *RobotLeavingNest* are also pseudo-boxes since this information must be exchanged with other pheromone RFID readers entrance.



Fig. 9. Petri net for tag N1 in semaphore 2.

The inhibitor arcs at *WriteGreenN1* indicates that if there is a robot returning to the nest, the robot leaving the nest must wait until that robot pass through tag N4. Theses inhibitor arcs are defined at microcontroller code.

The Petri net for tag N6 in semaphore 2 (see Fig. 10) has connection to the Petri net for tag N1 through the pseudo-box *RobotInTrailB*. Since tag N6 is only a tag that indicates the mobile robot has left the pheromone are, its net just reads the tag and send a pseudo-box every time it senses the robot at this position.



Fig. 10. Petri net for tag N6 in semaphore 2.

## 5 Conclusion

The paper presented how to integrate PN and RFID to emulate pheromone of ants. The iPNRD approach was used to reach the ant pheromone in swarm mobile robots requirements, it means, the iPNRD approach meets collision avoidance, it doesn't demand high battery power consumption, it has practical implementation and, introducing smart environment with embedded RFID readers, this approach generates independence between the environment pheromone and mobile robots. This solution requires clock synchronization between smart environment RFID readers and mobile robot readers.

RFID Tag data capture and RFID tag storing as viewed as pseudo-box means that they are message exchanging between both readers from environment and mobile robots.

The semaphore is a low-cost implementation due the cost of each reader being under U\$ 2.25 (price quoted on ebay). The system can use only one controller for

the entire semaphore, or each reader can have one controller attached. For this to be possible, the controller must have a master-slave communication protocol.

This approach shows that the pheromone is independent of the mobile robot, since its concentration only depends on the value stored in the tag. But the robot only can choose a path to follow if there is an information (trigger vector) stored on pheromone's tag.

For further works an analysis of the hardware must be considered just like the system implementation.

Changes can be proposed on pheromone algorithm and source algorithm to evaluate the robots' behavior when there is a lack of energy stored in the source, when the energy carried by the robot is variable, and when the pheromone concentration decreases according to different equations.

Also, it is possible to analyze the swarm behavior collectively or individually. When the nest is a FIFO queue if one robot stops, all the system is going to fail, but if the nest has an area to park each robot, when this robot stops the system continuous to work with any problem.

Lastly, a Petri net analyses must be considered regarding deadlocks, model checking and invariants.

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