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Autonomous and Distributed Control of Unmanned Aerial Vehicles

Work presented as partial fulfillment of the requirements for the degree of Bachelor in Computer Engineering.

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ABSTRACT

Because of the mobility, easiness of operation and the recent price reduction Unmanned Aerial Vehicles (UAV's) have, during the last few years, become technically and economically viable alternative tools to perform a great number of tasks classified as 3D - Dull, Dirty and Dangerous. These tasks are also characterized to be expensive and demanded a great deal of effort or equipment or that presented a high risk factor to human lives, such as remote imagery acquisition, perimeter surveillance, search and rescue operations after a natural disaster and military field operation.

Following this trend, the project in which this work is inserted aims to use a group or swarm of UAV's performing the role of mobile routing nodes in order to establish a reliable, flexible and efficient communication network. This network can be used as an alternative solution to provide support to operations located in environments in which a fixed or traditional communication network cannot be counted on or is unstable such as, for example, search and rescue operations after a natural disaster.

In this context the following work presents the development and the results of an algorithm capable of exploring the largest possible area of a map while being able to perform side missions, handle points-of-interest (POI) and maintain an active network link.

To achieve the desired behavior, two multi-agent social interaction algorithms were combined. The first consists on a potential map algorithm which is a modified vision of the biologically inspired ant-colony optimization method and it is responsible for the movement itself, handling the movement, area coverage and network connectivity problems. The second one is a contract algorithm based on a market economy paradigm and it is responsible to handle the tasks, missions and POI distribution between the UAV's.

Keywords: UAV. Multi-agent system. Mobile network connectivity. Swarm coordination. Market economy. Potential map. Ant colony.

Controle Autônomo e Distribuído de Veículos Aéreos Não-Tripulados

RESUMO

Devido a sua grande mobilidade, simplicidade de operação e à redução dos custos envolvidos em sua aquisição os Veículos Aéreos Não-Tripulados (VANT's) tornaram-se, nos últimos anos, ferramentas viáveis técnica e economicamente para inúmeras aplicações que eram anteriormente complexas, caras e de difícil realização ou que apresentem ameaça à vida humana, como por exemplo, monitoramento, sensoriamento e aquisição remota de imagens.

Seguindo esta tendência a proposta principal do projeto no qual este trabalho está inserido é utilizar um grupo de VANT's desempenhando o papel de nós comutadores móveis de forma a configurar uma rede de comunicações confiável, flexível e eficiente como solução alternativa para dar suporte à operações em ambientes e/ou cenários nos quais não se pode contar com um uma infraestrutura fixa de telecomunicação, tais como em locais afetados por desastres ou em situações de combate.

Neste contexto este trabalho apresenta desenvolvimento e teste, juntamente com os resultados, de um algoritmo de coordenação de movimento para VANT's que seja capaz de explorar a maior área possível de um mapa e executar missões paralelas enquanto se encarrega de manter um enlace sempre ativo nesta rede de suporte.

Para atingir estes objetivos dois algoritmos teóricos principais serão combinados em um algoritmo híbrido. O primeiro algoritmo é uma versão do biologicamente inspirado algoritmo de otimização de colônia de formigas, este será responsável pelas decisões sobre a movimentação dos agentes, coordenando o movimento, o problema de cobertura de área e os problemas de conectividade. O segundo é um algoritmo de leilão por economia de mercado, responsável pela distribuição dos pontos de interesse a serem visitados e das missões paralelas.

Palavras Chave: VANT, sistemas multi agente, coordenação de drones, economia de mercado, colônia de formigas, economia de marcado.

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LIST OF ACRONYMS AND ABBREVIATIONS

UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aircraft System
MAS	Multi-Agent System
SNR	Signal-Noise Ratio
RCPI	Received Channel Power Indicator
RSSI	Received Signal Strength Indicator
IEEE	Institute of Electrical and Electronics Engineers
POI	Point of Interest
WSN	Wireless Sensor Network
CNP	Contract Net Protocol
QoS	Quality of Service
FANET	Flying Ad Hoc Network
HALE	High Performance Long Endurance Unmanned Aerial Vehicle

CONTENTS

1. INTRODUCTION

Unmanned Aerial Vehicles (UAV's), also called drones, use in field missions has increased substantially during the last decade, many military and civil applications have been proposed and tested, their use has become more popular and technology evolution has brought these systems innumerous powerful capabilities. Because of these trends UAV's have become viable alternative tools, technically and economically speaking, to perform a great number of tasks that used to be expensive and demanded a great deal of effort or equipment, such as remote imagery acquisition or perimeter surveillance. Allied to the technical an economic benefits the use of UAV's in field missions has another extremely important characteristic: it helps reducing the risks to human lives in dangerous or wearisome scenarios and missions, increasing the performance and reducing the costs of such activities.

However, while some applications and activities can be easily performed using a single vehicle and a remote control or simple algorithms some other applications exist that require multiple vehicle systems interacting with each other and moving accordingly in complicated environments. This second type of application gives room to a vast research area covering fields like artificial intelligence, multi agent systems, network organization, optimization techniques and graph theory among many others that can be related to such scenarios.

In this context one of the most challenging problems concerns multiple vehicle coordination and interaction as some systems require a variable number of UAV's working together as to reach a goal or accomplish a task. This kind of system is the very perfect example of a multi-agent system (MAS), a system that should, dynamically and distributedly, come up with a strategy to perform a mission as a group allying performance, reliability, robustness.

1.1 Context of this work

Among the many applications multi-agent systems composed of drones may have some can be proposed that are of fundamental civil interest. In times of war or those right after some natural disaster like hurricanes or earthquakes a chaotic and harsh panorama is presented: search and rescue missions are needed in dangerous or perhaps inaccessible locations and basic infrastructure assets can, often, not be counted on or are not reliable.

Considering such situations, the project in which this work is inserted aims to use a group or swarm of UAV's performing the role of mobile routing nodes in order to establish a reliable, flexible and efficient communication network. This network goal is to be an alternative solution to provide support to operations located in environments in which a fixed or traditional communication network cannot be counted on or is unstable.

The overall system can be seen as a multi-agent system (MAS) that, working in a cooperative way, should allow the vehicles or agents, by themselves or in groups, to perform specific missions and, simultaneously, spatially organize themselves as to be able to maintain a reliable communication link between them.

In such a context the following work aims to present a possible movement coordination algorithm capable of exploring the largest possible area of a map while being able to perform side missions, handle points-of-interest (POI) and maintain an active network link.

1.2 Structure

Section 2 of this work presents the theoretical background used as a basis in the implementation, idealization, test and analysis of this work.

While Section 3 is reserved to the problem definition, presenting its properties and the characteristics that make it a challenge, Section 4 deals with related works and initiatives that can help when modelling a solution.

Section 5 presents a solution outline to the problem and deals with this solution modelling particulars, outlining techniques and explaining how each part of the problem is solved.

On Section 6 the implementation particulars are discussed, as well as the simulator implementation assumptions presented.

Section 7 brings the tests and results through a series of experiments and the results analyzed, being Section 8 reserved for the final considerations.

2. THEORETICAL BACKGROUND

2.1 UAV’s and UAS’s

UAV’s are, by definition, aerial vehicles, that do not need a human pilot aboard to control them, the control can be done remotely by a pilot or system making use of a remote control or locally by some kind of computer system embedded on the UAV itself.

Usually these vehicles have a central controller, often composed of a microprocessor and a piece of embedded software, responsible for the UAV resource management, control and communication with other entities. As so UAV’s can be furnished with a myriad of equipment, sensors and actuators granting them or the system they are inserted in a large number of capabilities and qualifications to perform different kinds of missions.

According to the Aeronautical Consultant Reg Austin (AUSTIN, 2010) an important difference to have in mind is that between an unmanned aerial vehicle (UAV) and an unmanned aircraft system (UAS). According to his definition the aircraft (UAV) must be considered as a part of a whole bigger system composed by the aircraft, the command modules, the communication modules, the aircraft payload and so on.

Also unmanned aircraft are different from model aircrafts, model aircrafts are defined as those which do not have any kind of embedded intelligence, it means they are built to execute pre-programmed missions and are usually not capable of handling unexpected situations. UAV’s, on the other hand are considered to be autonomous agents (see section 2.3.1 for a definition on agent) possessing some degree of artificial intelligence and decision making capabilities. UAV’s shall be able to communicate with other subsystems, return or receive data through communication and handle unexpected situation, such as communication failures without compromising the mission.

UAV’s can be classified according to their physical characteristics, such as size, weight, wingspan, flight altitude, endurance times, etc. The largest types, known as HALE’s (High altitude long endurance) are commonly used in military applications and can, in some cases, perform missions of more than 24h flying at up to 15.000m of altitude. These, however, require complicated infrastructures to fly and are usually operated by the military.

The most relevant types of UAV used today by civil and even some military applications are the mini-UAV's, these are usually light (less than 20 kg), small and fast to deploy, not required a lot of infrastructure to support a mission. Mini UAV's became popular because they have become cheap and have relatively good payload, endurance and range specifications, making them ideal to short missions on complicated or urban environments.

2.2 Game Theory and Auction Theory

Game theory is, according to Myerson (Myerson, 1991) "[…] the study of mathematical models of conflict and cooperation between intelligent rational decision-makers." Basically this field of mathematics tries to study, model and understand strategies and decisions used by agents when interacting with each other during a conflict situation while trying to "win the game", or, in other words, to reach the best possible outcome using their decisions.

One of the basic elements of a game is the set of players, each player has its own strategy that maps their decisions and uses this strategy to reach its preferred payoffs or outcomes. It is important to note that each strategy has a different payoff and choosing a specific strategy is up to the player and is based on the player's utility function that maps the payoffs to each of the game situations.

Game theory is widely used in many areas but its results are especially useful in business and economic analysis since they can help modeling competing situations and thus predicting the behavior of markets and outcomes of specific market situations. One example of these situations is an auction market, in which different agents try to buy goods or services by offering them up for bid, taking bids, and then selling the item to the highest bidder. These situations are studied by a field called Auction Theory.

2.2.1 Auction Theory

In their book about auction theory Menezes and Monteiro (MENEZES; MONTEIRO, 2005) define an auction as mechanism used by a market to balance supply and demand. According to their interpretation auctions are mostly used to sell goods or resources that do not have a solid or established market and have the important characteristic of having well known rules for price formation. These characteristics makes auctions, in their words "[..] more flexible than a fixed price sale and perhaps less time consuming than negotiating a price." (MENEZES; MONTEIRO, 2005, p. 10).

The authors also present some auction formats such as open auctions, the ones in which all bidders know each other's bids, and sealed-bid auctions, the ones in which the bids remain secret to the other bidders. Another type of rule or format is related to the price paid by the winner, common types are first-price auctions, where the winner pays the highest bid, and second-price auctions, those in which the winner pays the second highest bid for the resources being sold.

Auctions can have many sets of rules, among the many types of auctions that can be created combining these rules, some types are notable:

- English or ascending-price auction: open bid auctions in which the bidders increase their bids in turns until no bidder is willing to raise their bid above the current highest bid. It is probably the most common type of auction out in the world and is a first price auction (the winner pays the highest bid price).
- Sealed-bid auctions: Each bidder bids having no knowledge about the price offered by the other bidders, the winner is the contestant who offered the highest bid. One subtype of these type of auction worth mentioning are the Vickrey Auctions, presented by William Vickrey in 1961 (VICKREY 1961) it is a second-price sealed-bid auction.

- Dutch Auctions: used by Dutchmen to sell flowers it is perhaps one of the least common auction types. It starts with a high asking price which decreases over time until some bidder is willing to pay what the auctioneer is currently asking.

Munhoz-García, (MUNHOZ-GARCÍA, 2012) explains auctions as settings in which players have to choose their strategies in a limited information context. According to his work auction can be seen as resource allocation mechanism with two main rules: An allocation rule, specifying who gets the object after the auction; and a payment rule, describing how much the winner must pay.

2.3 Multi-Agent Systems and Task Distribution

2.3.1 Agents

One of the simplest definitions of an agent (WOOLDRIDGE; JENNINGS, 1995) defines it as a computer system which presents 4 basic characteristics:

- Autonomy: agents must be capable of operating independently of human intervention and have control over their actions;
- Social Skills: agents must be capable of interacting with other agents;
- Reactivity: agents must be capable of perceiving their environment and act accordingly;
- Pro-activeness: agents must not solely be capable of reaction to the surrounding environment but also should assume an opportunistic behavior acting as to reach their goals;

This concept was later reinforced by the same authors and adapted to provide a more general idea stating that: “[…] an agent is a computer system, situated in some environment, that is capable of flexible autonomous action in order to meet its design objectives […]” (JENNINGS; SYCARA; WOOLDRIDGE, 1998, p. 8)

2.3.2 Multi-Agent Systems

According to Jennings *et al.* (JENNINGS; SYCARA; WOOLDRIDGE, 1998) agent based systems are those in which the basic abstraction model is that of an agent. These agents are autonomous entities that can be or not heterogeneous in nature and may compose systems that contain more than one of them, the so called multi-agent system (MAS).

Still in this definition the authors expose an MAS as a network or group of agents that work together to perform a task or solve a problem that, for its nature or characteristics, cannot be performed by any agent alone. They also present some of the fundamental characteristics a multi-agent system should have:

- Each agent has insufficient data or skills to solve the problem alone, the agents are thus limited;
- There exists no global control on the system
- The data are stored in a decentralized structure
- The computation is asynchronous

2.3.3 Task Allocation and Distribution

According to our definition a multi-agent system is composed of various agents that work together to achieve a goal or perform a task. Each agent is, therefore, responsible for individual and specific tasks that are part of the overall solution. These attributed tasks can be performed with moderately efficient results depending on the agent skills, characteristics or internal state. So it becomes necessary for these tasks to allocated as optimized and conveniently as possible.

Task allocation can be then explained as the process of attributing a specific problem to be solved by a specific agent. This attribution can be static or dynamic, being the last case the most interesting one because it allows the system to allocate tasks according to the availability of the agents and to the available agents' characteristics.

Proposed by Davis and Smith (DAVIS; SMITH, 1983) the CNP (Contract Net Protocol) is one of the most know and used protocols to solve the task allocation problem, it is based on a market economy paradigm. A great number of extensions and adaptations were presented to modify the CNP since 1983. Some of them, like the ones proposed by Walsh and Welman (WALSH; WELLMAN, 1998) and by Gerkey and Mataric (GERKEY; MATARIC, 2002), modify the algorithm to make it work in a distributed way, while others introduce parallelism and fault tolerance, like the one proposed by Aknine et al. (AKNINE et al, 2004).

2.4 Networks and Connectivity

Communication networks can be represented by graphs in which the interfaces are the vertices and the links between them are the edges in which the messages travel. From graph theory comes the concept of a connected graph, a graph that contains a path connecting any point to any other point in the graph. This concept can be extended and used in the networking context defining a connected network as a network in which any two interfaces in the network can successfully send messages to each other.

Networks configurations accept many different topologies, it means that the special configuration of its interfaces and of the links between them can be diversified. These different topologies grant the network different characteristics: star topologies are organized around a central node through which all messages on the network go through; ring topologies often represent networks with bigger degrees of redundancy since once one link between two nodes is lost a connected network can still be achieved. Another important topology is the mesh topology, it has become more popular lately due to the popularization of wireless networks, to these networks there is no formation rule, each node connects to as many nodes as possible, configuring multiple routing paths for the messages and thus granting redundancy.

2.4.1 Wireless Networks

During the last few decades wireless communications have become extremely popular, its concept is simple: use the air as a physical channel to transport information though electromagnetic waves. This theory, besides simple, offers many challenges to the engineers responsible for these networks because, differently from the wired ones. As an example there is the fact that electromagnetic waves are subject to all kind of noise, attenuation, dispersion and even physical barriers, which bring an important discussion concerning signal strength and quality.

There are basically three main factors that influence signal quality:

- Signal Noise Ratio (SNR): a relation between the power of the electromagnetic signal and the power of the background noise. A great noise power prevents the receiver from correcting interpreting the signals received;
- Physical Barriers: it is known that depending on the material of the barrier and on the signals wavelength electromagnetic waves might be attenuated or even lost when going through objects or obstacles;
- Free Space Path Loss: electromagnetic signals are attenuated not only by physical obstacles but by the space itself so even having line of sight between the transceivers the power well drop between two ends of the channel.

To measure the signal quality received by a specific receiver, the industry has defined a kind of measure standard known as RSSI, or Received Signal Strength Indicator. The RSSI was supposed to be associated to the power seen by the receptor but its calculation usually lacks a formula and a standardization, having each manufacturer its own range and way to calculate this value. To solve this problem some systems have effectively created standardized metrics, like the RCPI metrics from IEEE 802.11k-2008.

2.4.2 Wireless Ad Hoc Networks

Ad hoc networks are basically those that do not rely on a fixed or preexisting physical infrastructure or administration. When speaking about wireless ad hoc networks specifically the notion is that the network does not possess a centralized access point or router to whom all other network nodes connect, instead every node can serve as a router or host, forwarding packets on behalf of other nodes and acting as network bridge.

Wireless ad hoc networks can be said to have some general characteristics more or less common to all of them, they must also be able to support certain situations related to network management as follows:

- Distributed operation: Ad hoc networks and nodes must be engineered as to support a distributed operation environment. They must include features to support, for example, distributed routing, since there is no centralized routing table. The same is valid for security.

- Dynamic network topology: In most cases, the nodes will be mobile, having at times a limited mobility and, at other times, an almost unlimited one, such as UAV’s or robots. These different mobility patterns and the mobility itself result in a varying network topology, and in variable routing tables as well, that must be handled without user interference or perception.

- Error correction: Because of the nodes mobility some disconnections or transmission errors are prone to occur, the system must so implement error correction and link maintenance algorithms to ensure that the network works correctly and that all data goes reliably through it.

- Power Management: in many cases, the network nodes will have power consumption limitations, most nodes on these networks can be, for example, battery driven. The algorithms and mechanisms that implement the networking functions into the devices must so be adapted to each device power consumption needs, allowing it to run applications and perform its tasks while still working on the network.

2.4.3 Aerial Networks

In their work Bekmezci et al (BEKMEZCI; SAHINGOZ; TEMEL, 2013) present the characteristics of flying ad hoc networks (FANET's). FANETS can be defined as ad hoc whose nodes are UAV's. However, not all networks composed by UAV's are FANET's, in order to be considered a FANET the communication between the nodes of a given network must be exclusively ad hoc, not relying in any infrastructure assets.

FANET's present some important characteristics that differ from the other common wireless ad hoc networks and that impact substantially on the network design and performance. One of these characteristics are the vehicles, different vehicles impose different mobility models and equipment, making the design and modeling of a generic FANET network a complicated task. Another characteristic is the high degree of mobility of the nodes, while most ad hoc networks have fixed or low-mobility nodes, UAV's move around at much higher speeds and have a greater degree of freedom concerning their movement. Autonomy is also a problem, UAV's are battery dependent and the power management must be always a concern. In addition to these characteristics there are always meteorological and atmospheric factors to be taken into account.

Additionally, the network requirements are greatly influenced by the application intended for the networks. Search missions require some QoS levels, exploration needs completely different levels and surveillance applications have yet another types of requirements.

The wireless technology is also an important factor, several technologies have already or are being investigated and their performance analyzed for use in FANET's. The most commonly used are IEEE 802.11 (Wi-FI) for data transfer applications and IEEE 802.15.4 (Xbee) for coordination and telemetry purposes, these choices are usually related to their costs and availability. Some later researches show that 802.11x modules satisfy most applications requirements and perform well on small FANET's, providing good QoS levels and throughput.

3. PROBLEM DEFINITION

As previously stated this works main goal is to present, implement and test a possible movement coordination algorithm capable of exploring the largest possible area of a map while being able to perform side missions, handle points-of-interest (POI) and maintain an active network link. Hence, in this context, missions have been defined in terms of two basic tasks: area coverage of a given perimeter; and, treatment of points of interest (POI) found inside this perimeter.

The system is composed by a limited number of agents (UAV's) so this problem starts to become non trivial once it is not only necessary to the system to maintain the connectivity of the network, cover or recognize an area and avoid collisions, but also to simultaneously or not allocate a subset of its agents to treat POI's and perform side missions. This complexity increases even more if the agents have different resources or skills between the, like different kinds of cameras or specifics sensors and actuators better suited to treat determined target. Such a context would make necessary for the system to be able to allocate specific agents to specific targets at specific moments while not comprising the mission, which is a hard problem to solve.

Side missions are defined as target based, it means that each side mission has an associated POI. These missions can be of varied nature and duration depending on the UAV's characteristics or skills, on the POI type, and on the overall requirements of the main mission. Some missions may require a single visit to treat a specific POI while others, like surveillance missions may require multiple visits to the same POI. The algorithm must be able to deal with both kinds of missions or situations.

Another problem the system must be able to deal with is the tradeoff between coverage performance and network connectivity. Since a nodes movement may cause its disconnection from the main network and connection quality and maintenance is highly dependent on the network topology and on the interfaces it is very hard, if not impossible, to ensure that both requirements, coverage and connection, are met with optimal performance.

Its highly probable that at some point the system conditions are such to make it impossible to ensure full functionality within a satisfactory amount of time. Once a situation like this is presented it becomes necessary for the system to have some heuristic or definition concerning which task or mission shall have the biggest priority. It is important to notice that such an approach may cause network disconnection of some node, coverage are overlap or even side missions to delayed.

Another important part of the whole system that has not yet been presented is the mission controller, a third party software module responsible for defining mission parameters and collecting the operator inputs. This works algorithm must be able to communicate with the mission controller module and receive from it the mission parameters, communicate it when POI's are found, receive orders regarding side missions and POI's and synchronously communication it of the mission status.

The last assumption made concerning this problem deals with simultaneity between the reconnaissance mission and the side missions. Side missions may be treated as they appear, during the reconnaissance mission, or may be performed after the end of the reconnaissance mission, the choice must be up the mission controller operator.

4. RELATED WORK

In their work Zlot et al (ZLOT et al., 2002) study and present a purpose of market economy algorithm to task allocation between various agents. Their purpose is based on target distribution between the robots, defining which targets each robot should visit. Each target is auctioned using the position of the robots and the mapped area as heuristics, granting the best possible coverage of their target perimeter.

Walsh and Wellman (WALSH; WELLMAN, 1998) present a distributed protocol of market economy to allocate tasks and scarce resources between agents. This solution is extremely interesting because it is able to ensure a good solution for auctioning problem in the absence of a centralizing auctioneer agent.

Following the same path Gerkey and Mataric (GERKEY; MATARIC, 2002) suggested yet another distributed auctioning protocol, called MURDOCH. This protocol aims to avoid bottlenecks and single points of failure in distributed systems and dynamic environments, like those composed of robots, known subjects to failures and malfunctioning.

In their study, Parunak et al (PARUNAK; BRUECKNER; SAUTER, 2005) exposed the biological concept of pheromones (biological markers) and their utilization in control and coordination of unmanned vehicles and robots. They treat the biological markers as agents capable of generating attractive or repulsive potential fields to rule the robots’ movements on the environment.

Sauter et al (SAUTER et al., 2005) study the performance and efficiency of pheromone systems in surveillance, search, and target acquisition applications. Their system is tested in distinct circumstances and is shown to be efficient in comparison to other methods, while not demanding complex adjustments for optimization.

In his work Paulo Haacke, (HAACKE, 2015) discusses almost the same problem presented by this work, an UAV coordination problem taking into account area coverage and POI handling. He employs two strategies to solve these problems: market economy paradigm auction and digital pheromone maps. Both solutions are tested and statistically compared considering their performances to solve the mentioned problems.

In 2014 Orfanus et al (ORFANUS; ELIASSEN; FREITAS, 2014) discussed in their paper the utilization of random movement coordination algorithms in self organizing networks to support wireless sensor networks (WSN). They analyze and test proactive and reactive algorithms developed to ensure connection between the moveable routing nodes.

In their studies Bekmezci et al (BEKMEZCI; SAHINGOZ; TEMEL, 2013) present the characteristics of flying ad hoc networks (FANET’s). These networks have some especial constraints that are discussed by the author and presented as challenges to be taken into consideration when working with these kinds of systems.

5. SOLUTION OUTLINE AND MODELLING

To solve the outlined problem, the idea on this project is to use a mixed strategy based on two different algorithms: an auction system based on a market economy paradigm and a biologically inspired pheromone map approached as a potential map. The first technique allows to allocate tasks and POI's to be treated by the different agents or UAV's of the system. The second algorithm is used to address the problems presented by the reconnaissance mission and network connectivity maintenance as well as coordinate the overall movement of the vehicles.

This hybrid solution is a combination of some of the algorithms found in the works of Section 4 applied together to ensure that all of the requirements of the solutions are met. The proposed pheromone method is based on Sauter's and mainly Haacke's work and extended to deal with the area coverage problem requirements. Similarly, the auction algorithm and task scheduling mechanism were mainly inspired in Haacke's work and Zlot's solution, being the timeout and retry feature the sole alteration from their original solutions. Finally the network connectivity maintenance is a simpler adaptation of the concept originally presented by Orfanus et al.

The aforementioned solution brings, then, nothing new to the table, it's main contribution comes in merging the individual solutions together and making them interact with each other as to grant a good behavior for the system as whole.

5.1 Solution Outline

5.1.1 Market Economy Paradigm

Market based systems are an important topic in the game theory, artificial intelligence and multi-agent systems study fields. These systems are often used as a task or resource allocation algorithm and are based on an auction market behavior. Once found a task, good or resource that can be sold or allocated to another agent an auctioneer, which is a special agent, will start an auction to define who will receive the product being sold. While the auction is open each agent is supposed to bid, based on its skills or another heuristic, and try to win the product, the highest bidder wins the auction and gets the prize.

In this project the resources to be auctioned will the points of interest and their associated side missions. When a POI is found the agent who found it should communicate the mission controller who, based on the POI's characteristics, is supposed to choose how to handle it and feedback this decision to the agents. According to the feedback they receive the agents will then start an auction to decide which UAV will handle the point.

This approach was chosen over other allocation and optimization techniques, such as simulated annealing, because it is an online method capable of reaching a good enough outcome in a given moment. Offline methods, such as genetic algorithms or simulated annealing are not suitable for such application because there is a great probability for system changes to occur between the method calculation and task execution moments. Because of these temporal constraints there is a need for the system to be able to reach the best possible results, which is not necessarily the optimal, given the system state in a given moment of the execution.

5.1.2 Potential Fields and Pheromone Maps

Ant colony and pheromone map algorithms are biologically inspirited algorithms. Copying the behavior of some types of insects these algorithms are based on the agents' capabilities to place and feel markers from a shared environment. These markers provide information for the others agents of the group helping them to choose their next actions, this practice often generates a good enough group behavior and coordination to let them accomplish whatever they are trying with satisfactory performance. Insects use biochemical substances as markers, these substances, in their case, are known as pheromones.

According to Parunak et al (PARUNAK; BRUECKNER; SAUTER, 2005) these algorithms can be applied using a potential field approach to command the movement of the moveable agents of a system. In their approach each point in the surrounding area has an associated field vector indicating the gradient of the potential field generated by the markers around it. Based on these vectors' orientation agent can then choose the best direction to move to in order to find a stable point on the field.

In this works context the purpose is to make the agents use the markers concept to infer data related to mission accomplishments and network status. Each agent is supposed to feel the active markers in the environment around it, process them and decide its next actions based on them. Using attractive or repulsive marker placements UAV's can communicate each other things such as movements needed to maintain network connectivity or which areas or POI's of the map were already visited as to maximize area coverage.

5.2 Overview of the Functional Sequence

Figure 1 shows the overall functional sequence of the algorithm. As stated on the problem definition (Section 3) there are two main modules, or actors to be considered: The Mission Controller Module and the UAV group or swarm. The first is responsible for mission parameters definition, while the second should deal with the mission execution itself.

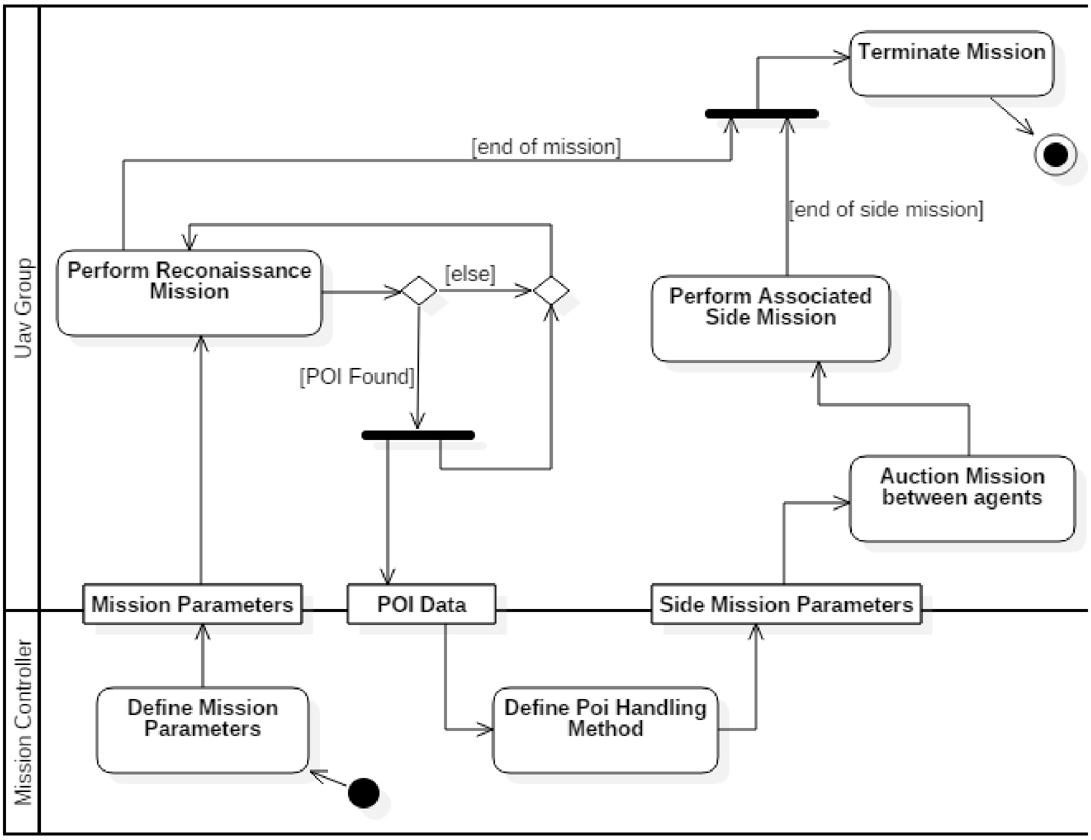
A mission execution sequence is composed of some main steps, as described on the listing below and diagramed on figure 1:

Listing 5.1: Mission Execution Sequence
Step 1: as a starting point the mission controller should define the mission parameters and communicate them to the swarm; Step2: the aircrafts should then start the recognition mission; Step2a: if found a POI the swarm should inform the mission controller module of its data and characteristics, if not the reconnaissance mission should continually normally with no changes to its state or status; Step 3: Once informed of a POI discovery the mission controller is responsible for defining the kind of treatment this point will receive and the side mission associated to it and feedback this information to the UAV group; Step 4: Having received information about how to handle a specific POI the swarm should then auction this mission as to choose the best fit agent to perform such a task; Step 5: The chosen agent is then responsible for the side mission execution; Step 6: Once ALL the side missions AND the main reconnaissance missions were terminated the mission should then be terminated;

Source: prepared by author

It is important to notice that steps 4 and 5 presented on listing 1 and step 2 can occur simultaneously or not, the simultaneity decision is up to the mission controller and its operator, being the only constraint that, when reached step 6, all the missions must have been successfully completed to proceed to the mission termination state.

Figure 1 - Overall Algorithm Functional Sequence



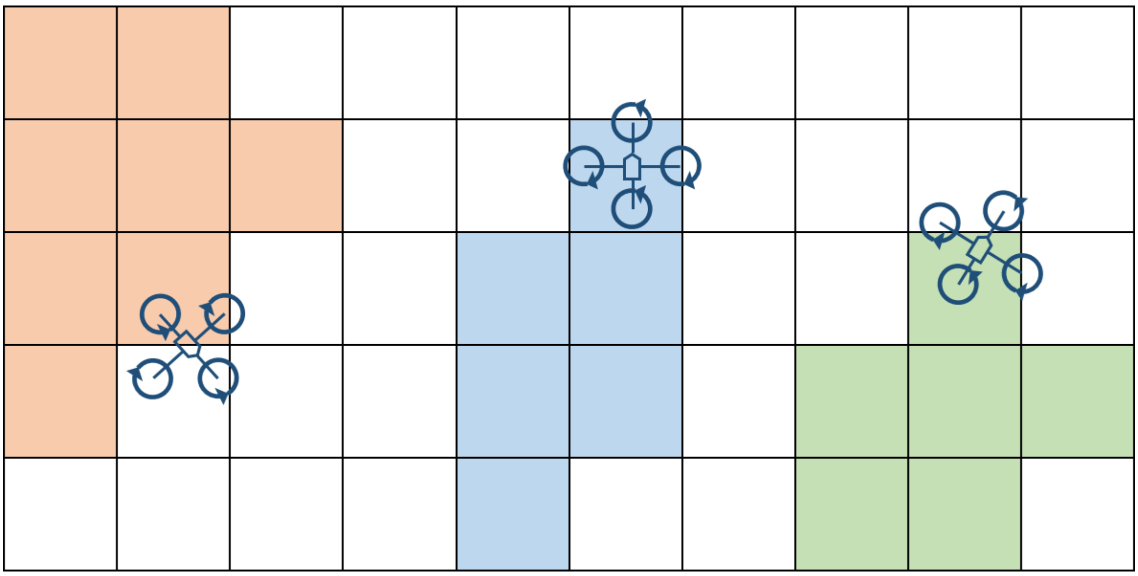
Source: prepared by author

5.3 Potential Map and Movement Calculation

Following the idea of using the pheromone concept and digital markers to solve the movement problem a sector map structure was implemented in order to map the markers placement from the environment. Basically the area to be covered was divided into many rectangular sectors. To solve the area coverage problem each sector must have less area than the UAV sensor used to capture the data from the ground is able to analyze during the time it is over that sector, it is done this way as to create a little overlap on coverage, making sure that no ground gets uncovered.

In this implementation each UAV has its own internal implementation of the map and each time a UAV enters a new sector it marks it with a repulsive marker and sends a broadcast message on the network informing the other UAV's of the marker deposition. Each UAV registers this information in its internal map and uses it to calculate its next movement, creating situations like the one shown in Figure 2.

Figure 2 - Illustration of three UAVs and their respective markers on a map.



Source: prepared by author

Each marker represents a potential field generator in space, movement is then calculated based on the orientation of the gradient vector of this field calculated on the point the UAV is currently at. Gradient vectors are vectors that indicate the direction and magnitude of the slope of a field or function in a given point of the space, using their orientation as a guide to the movement ensures that the UAV is moving as to avoid repulsive markers and visit attractive markers (see figures 3.1 and 3.2).

5.3.1 Potential Field Modeling

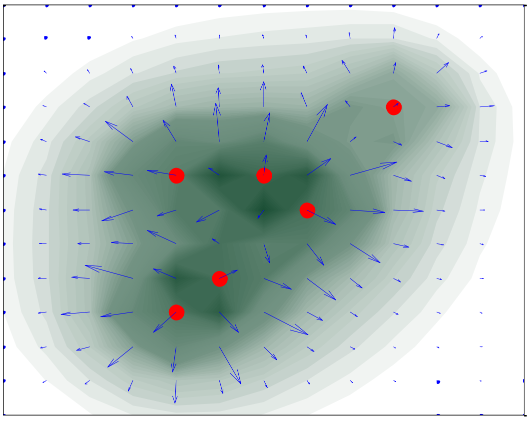
The potential field was modeled following an inverse square law, such as to reproduce a potential or electrical field behavior. The field magnitude created by a marker in relation to a UAV is proportional to the marker strength, proportional to the inverse square of the distance between them and also inversely proportional to the time passed since the markers placement on the map. Mathematically we have:

$$F = Me\hat{}(-kt)\ /d\hat{}2$$

Where F is the field magnitude on a given point; k is the proportional time constant for marker decay; $M$the original markers strength; t the time in seconds since the marker was placed and d the distance between the marker ant the interest point. The effects of the inverse square modelling can be seen on figures 3.1 and 3.2.

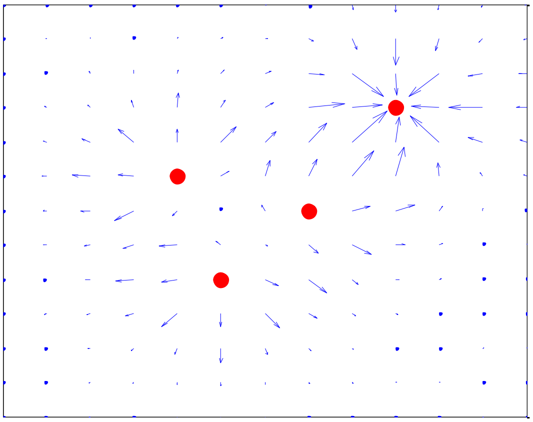
While the distance dependence ensures that each marker's field will have effect on the UAV movements only for a short parametrized distance, avoiding distant points to affect the appropriated local behavior, the temporal decay characteristics ensure that a sector that was previously visited a long time ago can be possibly visited again, increasing moving target's or recent new POI's coverage and contributing to movement smoothness.

Figure 3.1: Potential Field and Gradient generated by repulsive markers



Source: prepared by author

Figure 3.2: Potential Field Gradient generated by an array of markers



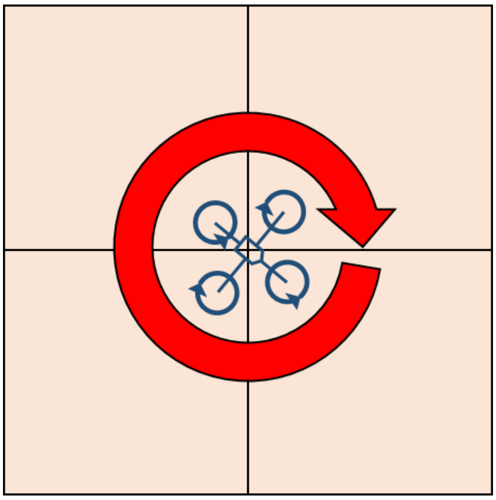
Source: prepared by author

5.3.2 Model Problems, Limitations and Solutions

This modelling by itself presents some problems, the first two are presented in figures 4.1 and 4.2. On figure 4.1 can be seen the first kind of problem presented by this modeling, four sector together, when creating a square such as in the figure originate a stability point on the center of this square, causing the UAV to remain almost static around that point. The second problem, shown in figure 4.2, is that in certain situation the field gradient causes UAV's to move in the centerline between sectors, never visiting their centers.

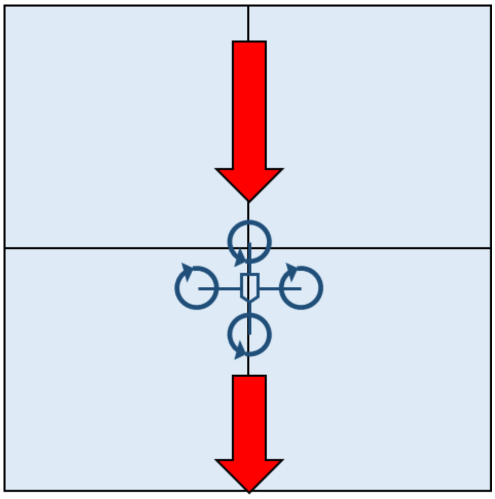
The third problem is presented by sudden turns, it was observed that in certain situations the potential fields ordered the vehicles to turn and change their moving direction by impossible amounts, sometimes even 180 degrees at once, something physically impossible for a UAV.

Figure 4.1: Stability point problem



Source: prepared by author

Figure 4.2: Movement on boundaries problem

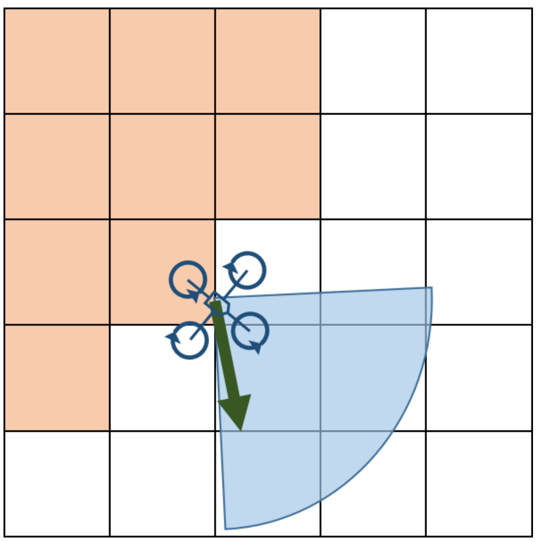


Source: prepared by author

A simple solution was implemented to solve these problems. Once the desired direction of movement was found the UAV is directed to the closest sector center in that direction. That means that it is directed to the one of the 8 sectors adjacent to the one it is currently in which center is closer to the desired direction of movement. To solve the sudden turn problem a limitation on which sectors can be targeted next was implemented, next sectors centers directions must not be more than 60 degrees dislocated from the current heading direction of the vehicle, if they are, the farthest sector on the appropriated range is chosen. Figures 5.1 and 5.2 show how it works representing the desired movement direction (figure 5.1) the angle limitation for next sector choice, and the next sector choice (figure 5.2).

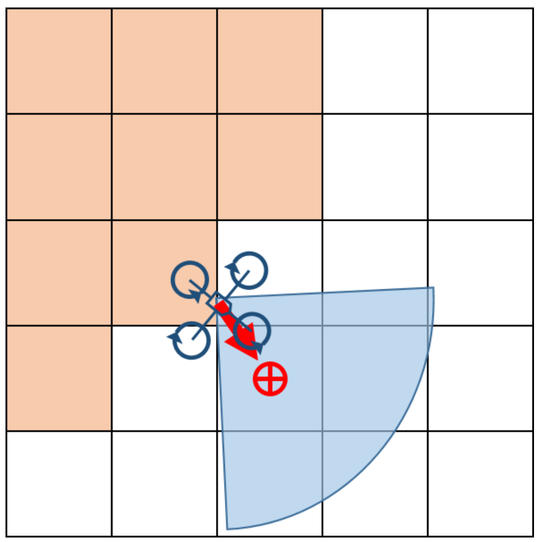
Also, large maps containing a large number of sectors can expose a limitation in terms of the computational resources used to calculate movement. Floating point calculations and some numeric methods are computationally intensive and are proportionally time demanding, making a lot of these in a row can imply in unsatisfactory temporal performances when dealing with some problems. As, in this model, the inverse square distance factor prevents significant contributions of distant sectors in the resulting potential gradient these can be safely ignored in the calculations without compromising the results, avoiding then these kind of temporal limitations.

Figure 5.1: Desired movement direction



Source: prepared by author

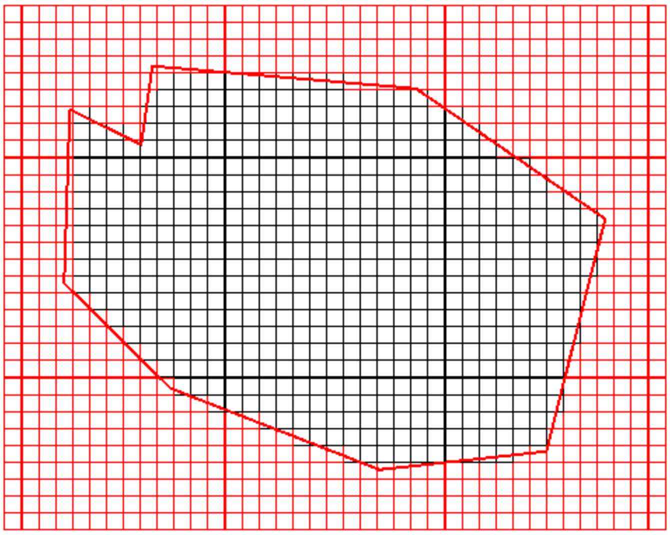
Figure 5.2: Real movement direction



Source: prepared by author

While considering a great number of sectors in the results may be time consuming, considering too few of them can also pose a problem, causing the system to assume incorrect behaviors. A solution to this limitation is parametrizing the system to use only a certain number of adjacent sectors around the one the UAV is currently at. Through an analysis of its contribution in the behavior of the algorithm this sector lookup parameter was found to be dependent on the average marker strength and on the average sector size. It does not, however, presents a great difficult once there is a certain flexibility on the range of values it can assume.

Figure 6: Sector map representation



1.190m x 1.598m area divided in 50m x 50m square sectors, of which 1.385.000sqm are visitable.

Source: prepared by author

5.3.3 Sector Map Implementation

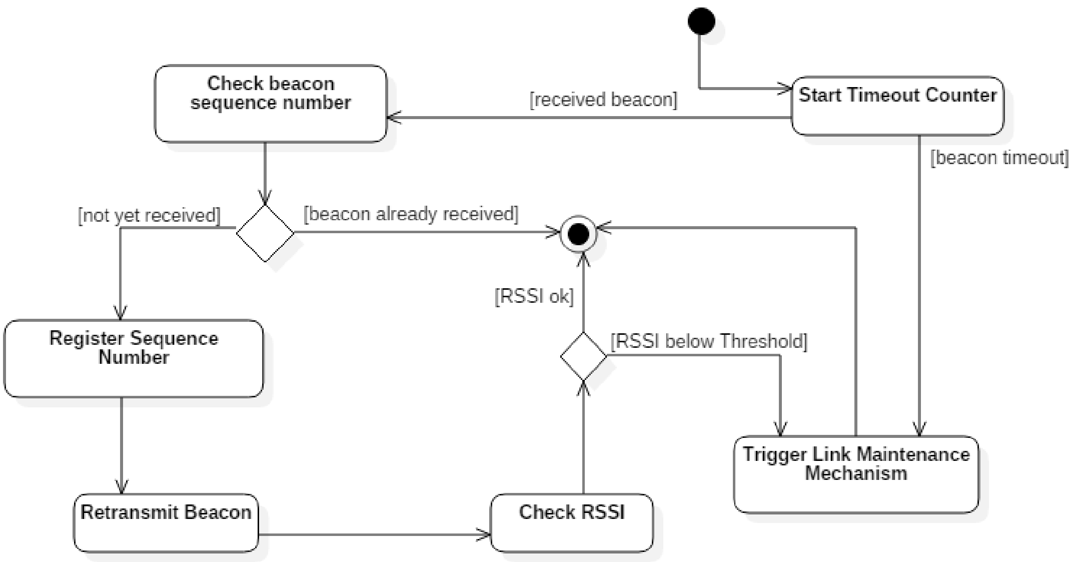
The sector map was modeled as a rectangular map composed of rectangular sectors covering the area of interest of a given mission. A group of extra super-repulsive-non-visitable sectors was added to each side of the map, this solution creates a gradient boundary and ensures that the vehicles will rest within the perimeter defined by the mission. Super-repulsive boundary sectors are also used to deal with non-regular surveillance perimeters: those sector which are outside the perimeter are automatically marked as super-repulsive. An example of this implementation can be seen on Figure 6.

5.3.4 Collision Avoidance by Pheromone Maps

This potential force model can be used to create a simple collision avoidance mechanism by applying a distance threshold condition to repulsive marker. If the distance between two UAV's drops below a certain threshold both associate a repulsive marker or potential source at each other's location, creating a repulsive force that will repel them. This only constraint this mechanism possesses is that the marker strength must be sufficient as to make the repulsion force made by the vehicles on each other stronger than the one created by the sector map markers, as to create a resultant gradient vector capable of repelling the UAV's.

5.4 Connectivity Maintenance

Figure 7: Proactive Link Maintenance Algorithm Flow Diagram



Source: prepared by author

Following the idea proposed by Orfanus et al (ORFANUS; ELIASSEN; FREITAS, 2014) a similar beacon-proactive link maintenance algorithm was implemented.

Basically a specific pre-determined agent of the system emits a heartbeat signal at fixed time steps, each of these is then broadcasted using the mesh network protocol as to reach all the agents connected to the system. Each beacon carries a sequence number whose objective is network flood avoidance. If a UAV receives a beacon with sequence number it has already received the beacon is not retransmitted, if not the agent retransmits it and analyses the beacon RSSI triggering or not the network maintenance mechanism accordingly. Also, if a beacon times-out the UAV automatically triggers the.

To analyze whether or not the connectivity maintenance algorithm should be triggered the beacon RSSI is compared against a threshold, if it drops below it the mechanism is activated, the mechanism is also activated in case of a timeout. The mechanism itself consists on associating an attractive digital marker source to the position of the UAV with the highest last received RSSI as to make the agent approach the other network node. This attraction point only constraint is that its strength (as modeled on 6.2.1) must be high enough as to make the UAV approach this point.

5.5 Auction System

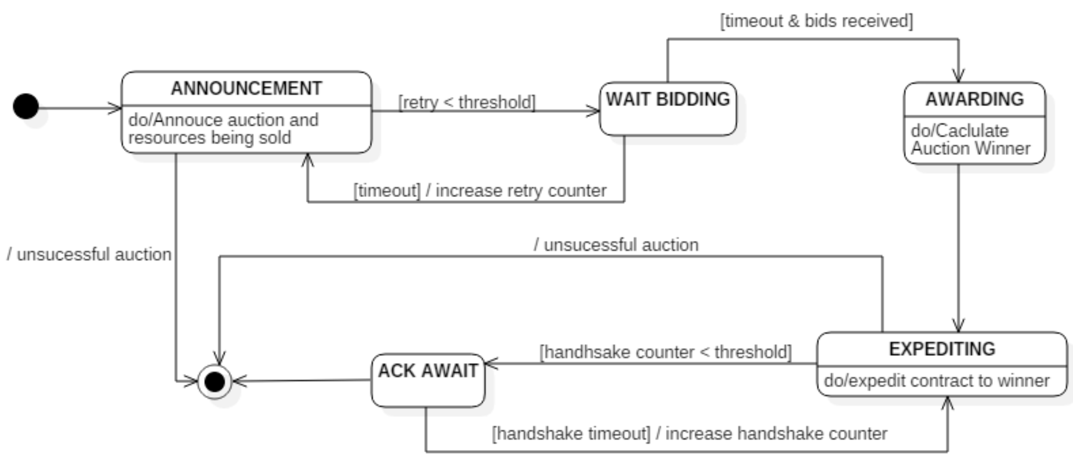
The auction system implementation is similar to a CNP protocol auction, except for the fact that the concept of a contract was somewhat simplified, for instance there is no contract follow up between the contract provider and the buyer here.

The auction system internal working is quite simple: there is an auctioneer agent and diverse buyer agents who bid their prices in order to gain some resource. The auction type chosen for this implementation was a first price sealed-bid auction, those in which each agent is not concerned with other agents' bids and the winner pays the highest price offered for the resource.

As can be seen in Figure 8 and auction section is composed basically of four main phases: announcement, bid awaiting, awarding, and contract expediting: On the announcement phase the auctioneer advertises through the network of possible bidders the start of a new auction session. It then waits for the bidders' bids for a certain amount of time during the bid awaiting phase. On the awarding phase biddings are analyzed, a winner is chosen and the bidders are informed of who the winner is. On the last phase, the contract is expedited to the winner giving him the right to use the auctioned resources.

Retry and timeout mechanisms were implemented during bid awaiting and contract expediting phases considering that some network disconnections may occur. Such a mechanism ensures that if an auction fails, it fails because no bid was made for the resource being sold and not due to some temporary network malfunction. During the contract expediting phase this retry mechanism is implemented through a handshake protocol, the winner has to send the auctioneer a confirmation that it has well received the contract before a timeout occurs. If a timeout is perceived the contract is resent and the handshake restarted, this process occurs 3 times before the auction is considered to have failed. On the other hand, during the bid awaiting phase, the auctioneer must receive at least one bid for the resources within a timeout period, Again, in case of a timeout, the section returns to the announcement phase and the process is restarted, this process retry limit is also 3, after that the auction is said to have failed.

Figure 8: Auction State Machine



Source: prepared by author

5.5.1 UAV Skill Register

In order to keep track of the tasks an agent is capable of performing a skill register was created. Using this system, each vehicle skills can be catalogued and mission or POI characteristics associated to these skills, allowing the biding and price formation rules to be abstracted and simplified.

To register a new skill some of its characteristics need to be informed, the most important are:

- Associated POI or type of mission;
- Cost to use this skill;
- Skill relative performance;

The first parameter indicates what kind of side mission or what type of POI this skill is capable of handling; the second parameter represents the cost, in arbitrary units, to use this skill; and, finally, the third important parameter is the skill relative performance when compared to the ideal case, this parameter was created because even if two UAV's have the same skills one of them can achieve best performance when using it due to external factors. Performance variations can occur for example because of different camera modules, some cameras can perform an image achieving operation significantly faster than others, affecting the mission outcome.

5.6 Task and Side Mission Handling

Because of the nature of the system it is impossible to foresee and determine which activities or tasks an agent may have to perform at a given period of time. Some tasks are location dependent, others have different levels of priorities and some are even time related (such as timeouts) creating so a high level of uncertainty. Another limitation tasks and missions bring to the surface is the need to sometimes perform two different actions logically simultaneously. Let's suppose that, in a given time, an auction may be in course while a UAV tries to photograph a given POI, in this situation the UAV cannot wait until the auction bid awaiting phase times out before it continues the image acquisition, it should do both things simultaneously.

To solve this task schedule problem a task scheduler mechanism was developed, basically a task can be seen a state machine piece of code that necessarily must output its external state to a task scheduler agent. A task external state is the tasks state as seen from the outside, for example, if we consider an auction section as a task, which it is, the task scheduler does not need to know if it is in the announcement or awarding phase, it only needs to know that it is running.

Four main external states were defined as shown in table 6.1. RUNNING an BUSY state were created to differentiate states in which a task execution can be broken or not. It makes no sense to stop all the system task executions when a specific task is waiting for a timeout, the scheduler can return back to it later and verify if the timeout has occurred, so it puts this task in the BUSY state. However, an image acquisition task cannot be stopped midways, so the scheduler attributes the RUNNING state to it. See listing 6.2 for a pseudocode representation of the scheduler behavior.

Table 5.1: Task external states

State Name	*Description*
WAITING	Task waiting to be executed, execution can depend or not of external factors
RUNNING	Task being executed, scheduler cannot proceed to next task
BUSY	Task running or being executed, scheduler can proceed to next task
FINISHED	Task execution finished, scheduler can proceed to next task

Source: prepared by author

It is important to notice that every non movement-related activity of a given UAV is, by definition, a task in this context, side missions and POI handling are tasks, as are auction sections, sensor readings and actuator activations. Another important point is that, as can be seen in Listing 6.2, tasks execution can extend during multiple algorithm cycles, and, as long as they do not block other tasks execution for extensive amounts of time, have no time limitations whatsoever.

Listing 5.2: Task Scheduler Behavior

```
select next task on the scheduler list.
case task state:
        is WAITING:
                verify if the execution conditions are met (such as location, time, etc);
                if conditions met, execute task;
                if not proceed to next task;
        is RUNNING:
                wait while task finishes or changes state;
        is BUSY:
                verify if the task has conditions to change state met;
                if conditions met, change task state;
                        if new state is RUNNING or WAITING execute task;
                if not proceed to next task;
        is FINISHED:
                remove task from the scheduler list;
                proceed to next task;
```

Source: prepared by author

6. SOLUTION IMPLEMENTATION

6.1 Overall Implementation

Following the solution modelling presented on Section 5 there has been created an implementation plan for the algorithm in order to ensure that it could be run across multiple platforms and target both simulated and physical tests and experiments.

The system implementation was made using Java Language version 8 due to its resources and abstractions. Java possesses some easy-to-use graphic and network libraries it seemed the most fit language to be used on the preliminary implementation. Because of these abstractions and libraries Java enables the developer to concentrate his efforts and focus on the algorithm part itself, not having to deal with graphic, network or other complicated algorithms that are not the main parts of such an implementation.

On the algorithm context itself some assumptions had to be made in order to ensure a complete and correct implementation. The most important of these assumptions concerns the agents, each agent on this work's context had to implemented as a completely separated software module or process. This implementation assumption implies that the agents are not able to see each other internal states, making exclusive use of the communication channel to access this kind of information.

As for interfacing with the external world each agent had implemented two interfaces inside it: a communication and a physical access interface. The first was created as an abstraction of the communication interface, granting the programmer the ability to send or receive messages through the network without having to mind network specifics. The second was made as to abstract the UAV physical interface, enabling the programmer to receive information such as location, speed or altitude through simple functions instead of through vehicle's specific routines.

6.2 Simulator Environment

To test and realize the experiments an ad hoc custom simulator was created. Some simulators exist on the market that simulate some of the specific parts of the system, but none was found capable of simulating all the environment variables needed to correct test the proposed solution. The implemented simulator was developed, then, as to be able to simulate POI apparitions, mesh network behavior and UAV's physical movement behavior as best as possible.

The POI handling module was developed simply as a random GPS point generator that created random points. One of these random POI's was, then, returned when a UAV sensor was found to be over the sector where the POI was located, simulating a POI discovery.

The network simulator consisted on a message distribution algorithm that kept a list of the network node locations and, based on a path loss model, decided when a message should be sent or not between any two nodes. This module was created to simulate a mesh network, so it was equipped with an advanced routing protocol and tables in order to secure correct routing between two nodes that are not necessarily connected to each other by a physical link but have, nonetheless, a path between them.

And, finally, the physical behavior module consisted of a special piece of code capable of simulating the correct physical behavior of a real aircraft. This module made use of a numeric integrator and some control methods to calculate position changes between any two time steps of simulation. This system was fed with real life parameters and took into consideration the orders gave by the main control algorithm to move the aircraft around.

7. EXPERIMENTS AND RESULTS

To test the performance and results of the proposed solution some experiments were idealized and run. The first of these experiments analyses the performance of the proposed pheromone map algorithm and compares it to a random movement algorithm. The second experiment tries to analyze the connectivity maintenance mechanism by comparing three different parametrizations and their outcomes. The third and last experiment was idealized to simply test the auction algorithm and verify if it is working correctly.

The following sections present the parametrization choices and the experiments themselves, the obtained results and their analysis.

7.1 Target Platform and Tests Overall Parametrization

The experiments were parametrized accordingly as to simulate the behavior of the Iris+ quadcopter, a mini-UAV manufactured by 3D Robotics acquired to be used on the future phases of this project. The Iris+ 950 kV motors are capable of accelerating the 1282g UAV to around 70km/h, the flight autonomy stands between 16 and 22 minutes, depending on the payload.

Also the quadcopter will be equipped with an 802.15.4 Xbee radio module. These modules come in two versions, the mainstream Xbee, which features a 1mW transceiver capable of an outdoor transmission range of about 100m and the XbeePro variation, which features a 60mW radio module, whose range can approach 1600m in good outdoor conditions.

Considering these informations the tests were parametrized as follows: the number of UAV’s was set to five; the simulation time was set to 15minutes, one minute less than the minimum flight autonomy; the maximum UAV speed was set to 20m/s, which translates to 72Km/h, which is the top speed of the Iris+; the map sectors were sized 15m x 15m; the radio considered was a simple Xbee module, the one with a 1mW transceiver; and, finally, the simulation area was set as regular square of 1200m x1 200m. Follows an overview on Table 6.1:

Also, to model the correct radio propagation and add path loss simulation in order to calculate and verify the RSSI values during the simulation a log-distance path loss model was implemented in the simulator.

Table 7.1 Main Simulation parameter

Simulation Area	1200m x 1200m
Sector Size	15m x15m
Number of UAV's	5
Simulation Time	15 minutes (900s)
UAV Maximum Speed	20m/s
Radio Emitter Power	1mW (0 dBm)
Radio Receiver Sensitivity	-92 dBm
Radio Propagation Model	log-distance path loss model

Source: Prepared by Author

7.2 Pheromone Algorithm and Area Coverage

To verify the pheromone algorithm performance as a solution to the coverage problem the implemented algorithm was tested and compared against a random movement algorithm. The random algorithm works with a fixed time step random direction change, in this case it was developed to change its direction each 10 seconds by a maximum of 45% degrees.

The test was planned to be run 100 times for each of the algorithms, granting a good results pool for the analyses to be based upon. Likewise, it is interesting, before analyzing the results, to predict the desired outcome for the tests in order to verify the results correctness. Based on the system's parametrization it is expected from the pheromone map to be more efficient than the random algorithm method. Also, the result of the total coverage is not expected to reach more than 93,75%, which is the maximum theoretical coverage possible for the parametrized perimeter in 15minutes considering 5 UAV's at a constant speed of 20m/s.

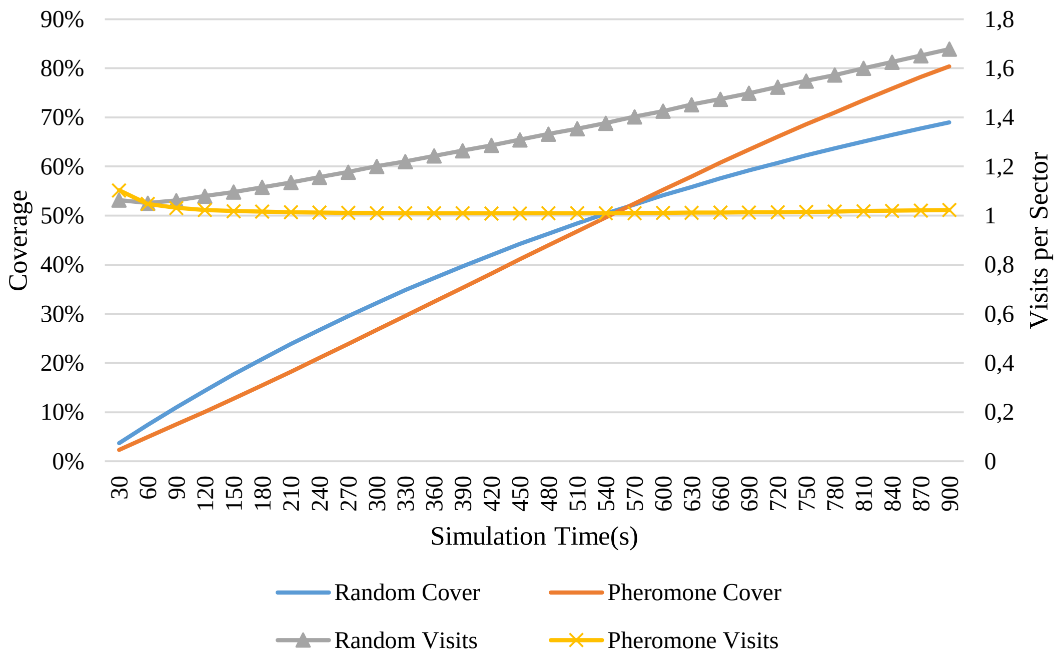
Table 7.2 shows the results obtained during the simulations. As expected the pheromone algorithm was more efficient than the random one, terminating the simulations (900s column on the table) with an average of 80,40% of the total area covered, against an average of 68,96% achieved by the other method.

Table 7.2 Random and Pheromone Methods Comparison

Simulation Time	150s	300s	450s	600s	750s	900s
Random: Average Coverage	17,66%	32,22%	44,22%	54,12%	62,28%	68,96%
Pheromone: Average Coverage	12,75%	26,74%	41,09%	55,26%	68,61%	80,40%
Random: Average Visits	1,10	1,20	1,31	1,43	1,55	1,68
Pheromone: Average Visits	1,02	1,01	1,01	1,01	1,02	1,02

Source: Prepared by Author

Figure 9: Coverage and Visits per Sector over Simulation Time



Source: Prepared by Author

Table 7.2 also shows the average visits per sector performed by each of the algorithms. As expected the random method performed more visits to each sector because it is not capable of choosing non visited sector to visit next as the pheromone algorithm map does. This sector choice behavior, however, causes an interesting result: During the first minutes of the simulation the random movement method presents better coverage results, it happens due to the fact that it does not waste time moving around and choosing sectors, being able to visit a greater number of sectors in a shorter period of time. As the simulation runs, however, the number of visited sectors increases, so does the visit overlap performed by the random algorithm. This situation decreases this method performance abruptly, while the pheromone map method continues to cover new areas almost in a linear way. A graphic representation of this behavior can be seen on Figure 10.

7.3 Connectivity Maintenance Mechanism

To verify the performance of the implemented connectivity maintenance mechanism three test scenarios were elaborated and simulated a 100 times each. In each scenario the RSSI threshold that leads to the triggering of the mechanism was changed. These parameters were set in terms of the minimum receiver sensitivity, which is -92dBm, being chosen the values of +3dBm, +5dBm and +7dBm above this level as the thresholds (Table 7.3).

Again it is interesting to try predicting the theoretical results before analyzing the experimental ones. Considering the implemented mechanism, it is to be expected that the simulations run with the +7dBm parameter present the better results and the ones parametrized with +3dBm the worse. Also, the connectivity maintenance mechanism is supposed to influence the area coverage performance for worse.

Table 7.3: Connectivity Test Parameters

	Parameter	*Real Threshold*
Simulation Scenario 1	+3 dBm	-89 dBm
Simulation Scenario 2	+5 dBm	-87 dBm
Simulation Scenario 3	+7 dBm	-85 dBm

Source: Prepared by Author

It is important, before analyzing the simulations results, to define the metrics to be used to analyze this situation. As the algorithm aims to have the maximum number of nodes connected each time, the defined metric, the connectivity number, is then the average number of connected nodes during the simulation.

It can be confirmed in table 7.3 that the +7dBm parameter has shown the best results, being centered around an average of 4,92 connected nodes, followed by the +5dBm with an average of 4,9 connected nodes. As predicted the +3dBm parameter has shown to have the poorer performance, achieving only an average of 4,84 nodes connected during the simulations.

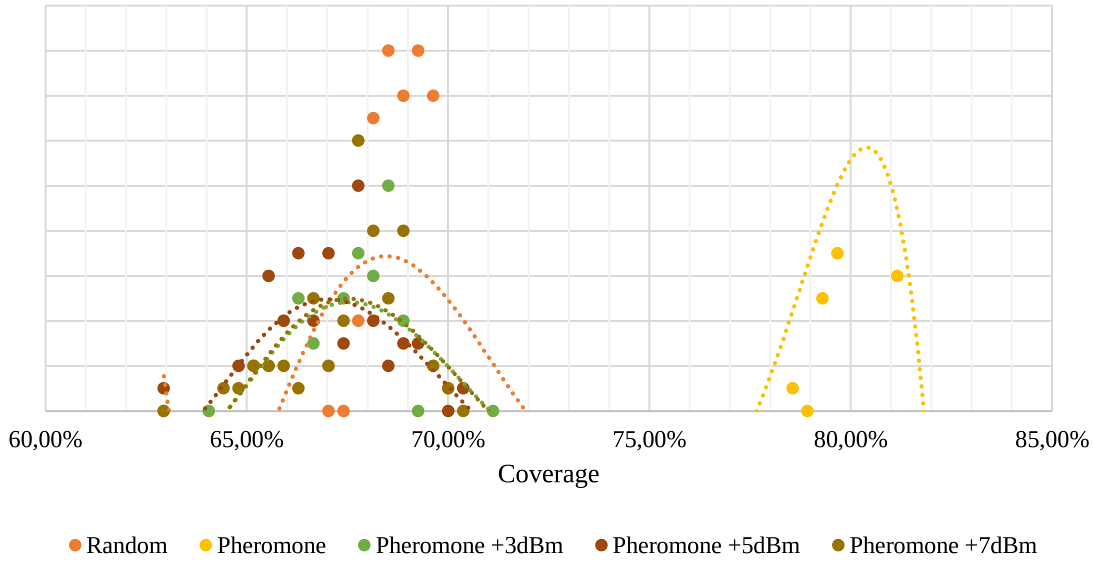
Table 7.4 Statistics of the Connectivity Maintenance Mechanism Simulation

	3 dB	*5dB*	*7 Db*
Average Coverage	67,52%	67,24%	67,57%
Average Number of Connected Nodes	4,84	4,90	4,92
Average Distance Between Nodes	45,81	50,08	55,02

Source: Prepared by Author

Also, as predicted the connectivity maintenance mechanism has compromised the area coverage function, lowering it to around 67,5%, even worse than the random algorithm approach. While this behavior was expected the comparison of the three different threshold levels presents a small variability, a strange result since it was expected that different levels should provide different area coverage statistics. Further testing is still required to determine the causes of this behavior, but it is believed that the sector size parametrization and the physical parametrization of the radios on the simulator are strongly related to this occurrence. A comparison of the coverage between the pheromone methods with and without connectivity maintenance and the random connectivity algorithm can be seen on Figure 10.

Figure 10: Coverage Comparison Chart

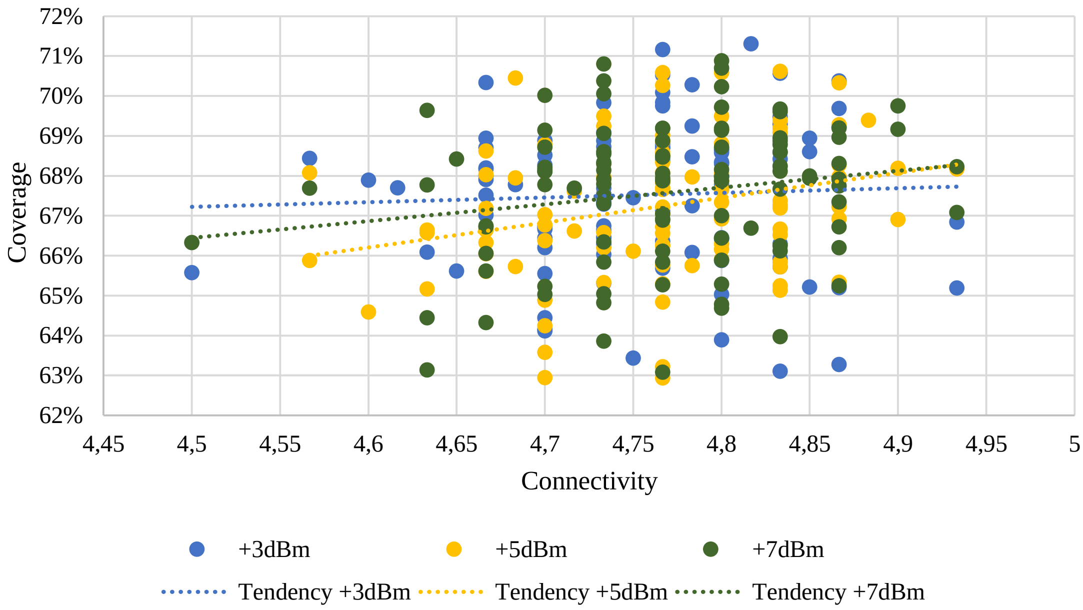


Source: Prepared by author

Another interesting result was the correlation between the connectivity and the area coverage. According to the results analyses greater connectivity implies greater coverage as shown in figure 11. It is possible that these results are due to the fact that when there is better connectivity the system is less prone to trigger the connectivity maintenance mechanisms to approach the nodes, leaving them free to move around and explore the surrounding sectors. This same correlated behavior was observed when the distance between nodes was analyzed in function of the connectivity, see figure 12, better connectivity implies in greater distance between the nodes.

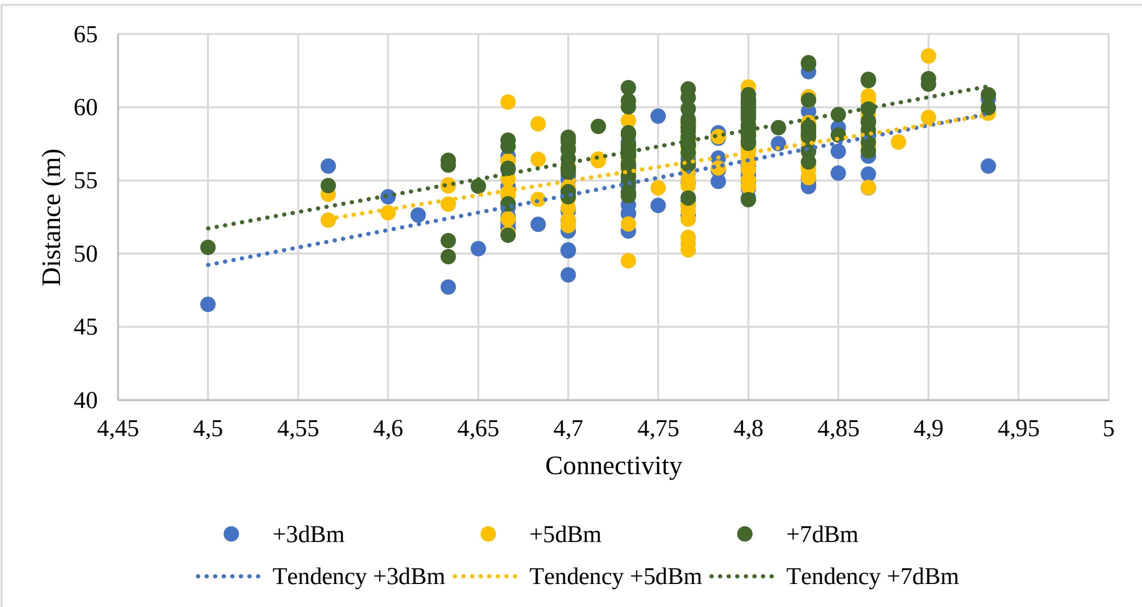
Additionally, it was observed that the system, as parametrized made the nodes move in a coordinated swarm formation, being the nodes never too distant from each other and always well grouped around a central point. This behavior may be good if the mission goal is to enforce connectivity, but can present a hard challenge if the goal is to ensure area coverage.

Figure 11: Coverage and Connectity Correlation



Source: Prepared by Author

Figure 12: Distance and Connectivity Correlation



Source: Prepared by Author

7.4 Auction Algorithm Verification

In order to verify if the auction algorithm works correctly a system consisting of 4 target types and 4 sensors, each capable of dealing with its associated target was implemented. The goal of this system is to verify that only the agents possessing a determined sensor A can win the rights to deal with targets of type A

Not only each agent has an associated sensor, but it has also a relative performance level varying from 30% to 100% that indicates the sensor performance. Less performance indicates that the sensor consumes more time, and consequently more battery to deal with a determined target.

Each agent's bid for a target is, in this simulation, calculated in terms of how much battery it can allocate to deal with the target being auctioned, meaning that agents with more battery bid higher. Each agent starts with a battery level of 100 and each sensor cost to operate per unit of time is considered to be 4, so, mathematically:

$$Bid_{Price} = 100 - \frac{4}{sensor_{performance}}$$

It is important to remember that each agent can only bid for a target that it has a sensor capable of dealing with. Each target type and agent sensor was initialized randomly as to insert no bias on the simulations.

A total of 417 different auctions were run, of which 264 were successful and 153 failed because no agent was found in the system with a sensor that matched the auctioned target. No auction was reported to have failed due to network problems, it is so probably because of the implemented retry and timeout mechanisms in the auction system.

Table 7.4 shows the appropriate results as found during the simulations, in this example agents with Sensor 1 won type 1 targets 62 times bidding an average of 81,32 points of battery, having no other agent with a different sensor won it nor bid for it.

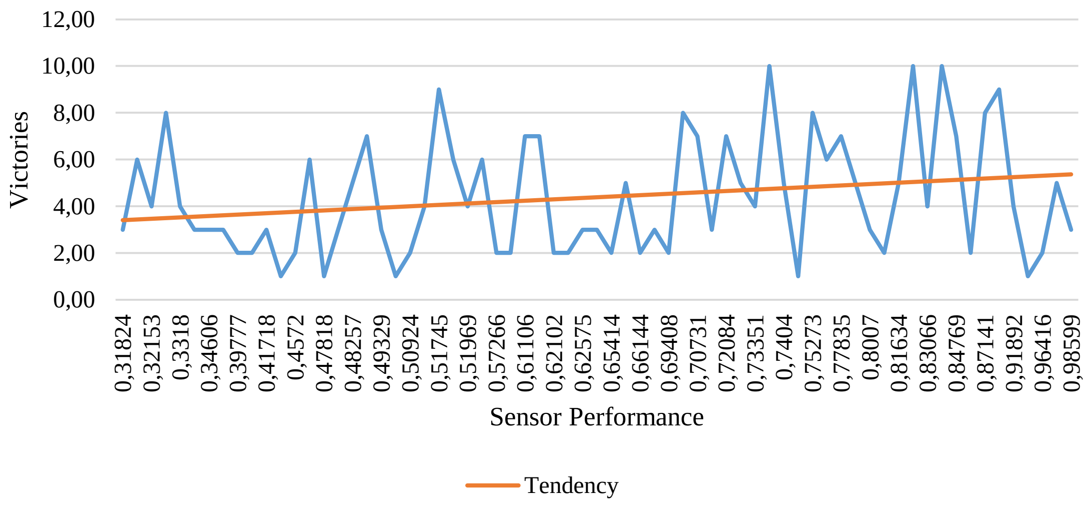
Table 7.5 Auction Verification Results

Sensor Type	Stats	Target Type 1	Target Type 2	Target Type 3	Target Type 4
	Bid Price Average	81,32	-	-	-
1	Victories	62	-	-	-
	Bid Price Average	-	77,56	-	-
2	Victories	-	121	-	-
	Bid Price Average	-	-	72,07	-
3	Victories	-	-	80	-
	Bid Price Average	-	-	-	80,44
4	Victories	-	-	-	31

Source: Prepared by Author

Also, as expected, agent with better performant sensors won statically more auctions than the ones whose sensors had a poorer performance. This result was already expected because, as already stated, sensors with less performance consume more battery to perform a task, having less battery left to bid on the next round. This result is shown in Figure 15. An important thing to notice in this situation is that battery used in the UAV movement was not taken into account in these tests.

Figure 13: Sensor Performance Vs Victories



Source: Prepared by Author

8. CONCLUSION AND FUTURE WORK

This work has present from its initial research to the its final results the implementation and testing of an algorithm idealized to dynamically coordinate unmanned aircraft systems to handle simultaneously area exploration, connectivity management and mission allocation problems. In this context the proposed solution merged multi-agent system, artificial intelligence and optimization methods into a unique unified solution capable of fulfilling the outlined needs while attaining a good computational performance.

To address the area coverage and exploration problem the implemented pheromone map solution has presented satisfactory results, allowing the UAV's to move around and explore an area as broadest as possible while avoiding a significant coverage overlap. When allied to the network maintenance algorithm this method has once again shown a promising behavior, obtaining almost the same coverage power of a random movement method while still ensure a reliable network link.

The auction system has also shown promising results, being able to correctly allocated targets between different agents based on a pre-specified heuristic, being an important auxiliary tool the movement coordination system.

Overall, considering the outlined context, the implemented solution has presented a solid and satisfactory behavior when it comes to addressing the challenges proposed. This solution is, however, highly dependent on correct parametrization, what makes it difficult to be used in some situations or very time consuming in others. Parametrization presents, so, a good subject for further study and work concerning the presented approach.

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APPENDIX A – FIRST SEMESTER WORK PAPER

Controle Autônomo e Distribuído de Veículos Aéreos Não-Tripulados

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- ***Abstract.*** *– Development of an autonomous and distributed movement coordination algorithm for Unmanned Aerial Vehicles capable of maintaining a reliable communication network between them while allowing these same vehicles to perform specific missions of various characteristics.*

Resumo. *Desenvolvimento de um algoritmo autônomo e distribuído de coordenação de movimento para Veículos Aéreos Não-Tripulados (VANT's) que seja compatível com a manutenção de uma rede de comunicação por eles formada e que permita paralelamente a execução de missões específicas de variada natureza por estes veículos.*

- **1. Introdução**

Devido a sua grande mobilidade, simplicidade de operação e à redução dos custos envolvidos em sua aquisição os Veículos Aéreos Não-Tripulados (VANT's) tornaram-se, nos últimos anos, ferramentas viáveis técnica e economicamente para inúmeras aplicações que eram anteriormente complexas, caras e de difícil realização, como por exemplo, monitoramento, sensoriamento e aquisição remota de imagens. É importante também observar que, por sua mobilidade e caraterísticas, os VANT's acabam por diminuir a ameaça à vida humana ao realizar missões em ambientes de alto grau de risco, e também por diminuir o custo envolvido e melhorar o desempenho de tais missões.

Seguindo esta tendência a proposta principal do projeto no qual este trabalho está inserido é utilizar um grupo de VANT's desempenhando o papel de nós comutadores móveis de forma a configurar uma rede de comunicações confiável, flexível e eficiente como solução alternativa para dar suporte às operações em ambientes e/ou cenários nos quais não se pode contar com um uma infraestrutura fixa de telecomunicação, tais como em locais afetados por desastres ou em situações de combate.

O sistema em questão é, então, visto como um sistema multiagente (SMA) que, operando cooperativamente, deve permitir que os veículos, individualmente ou em grupos, realizem missões de natureza diversa a eles designadas e, simultaneamente permitir que estes mesmos veículos se organizem espacialmente de forma a garantir enlace de comunicação aos usuários da rede configurada por ele.

Assim sendo, a proposta deste trabalho consiste na elaboração de um algoritmo distribuído de coordenação de movimento para este grupo de VANT's baseado em SMA's. Para realizar a solução deste problema não trivial a estratégia será baseada em algoritmos de inteligência artificial e otimização que deverão garantir a robustez do sistema e o desempenho na realização de missões. Esta solução será combinada também à algoritmos de análise e conectividade de redes de forma a assegurar o bom funcionamento da rede de comunicação.

- **2. Contextualização e Fundamentação Teórica**

- **2.1 VANT's**

VANT é normalmente todo aquele veículo aéreo que não necessita da presença de um piloto em seu interior para sua movimentação podendo ser controlados autonomamente por computador ou à distância por um piloto. Um VANT conforme esta definição pode vir equipado com inúmeros tipos de equipamento, conferindo a ele diversas habilidades e consequentemente uma grande gama de possiblidades de missão a ele ou ao sistema em que está inserido.

- **2.2 Sistemas Multiagente e Distribuição de Tarefas**

- 2.2.1 Agentes

Um conceito simples de agente apresentado por (WOOLDRIDGE; JENNINGS, 1995) define um agente como um sistema computacional que possui 4 características básicas:

- Autonomia: agentes devem ser capazes de operar de forma independente da intervenção humana

- Habilidade Social: agentes devem ser capazes de interação com outros agentes
- Reatividade: agentes devem ser capazes de reagir a impulsos percebidos do ambiente que os rodeia e reagir aos mesmos de forma adequada
- Pro Atividade: agentes não devem ser capazes somente de reagir ao ambiente, mas também devem exibir comportamento oportunista, agindo de forma orientada a objetivos e tomando inciativas próprias quando apropriado.

Em (JENNINGS; SYCARA; WOOLDRIDGE, 1998) os mesmos autores reforçam esta definição adaptando-a da seguinte forma: Um agente é um sistema computacional situado em determinado ambiente que é capaz de realizar ações autônomas e flexíveis de forma a atingir os objetivos aos para os quais foi projetado.

- 2.2.2 Sistemas Multiagente

Segundo (JENNINGS; SYCARA; WOOLDRIDGE, 1998) sistemas baseados em agentes são aqueles em que o modelo de abstração básico é aquele representado por um agente. Estes agentes são entidades autônomas e que podem ser heterogêneas em sua natureza, podendo também formar sistemas que contém mais de um agente, os chamados Sistema Multiagente (SMA).

Ainda em sua definição os autores apresentam um Sistema Multiagente (SMA) como uma rede ou grupo de agentes que trabalham em conjunto para realizar uma tarefa que, por sua natureza, não é solucionável por qualquer agente individualmente. Neste mesmo trabalho são apresentadas algumas das características fundamentais de um SMA:

- Cada agente possui informações ou capacidades insuficientes para resolver o problema, assim cada agente é limitado;
- Não existe um controle global do sistema;
- Os dados encontram-se descentralizados;
- A computação é assíncrona

2.2.3 Distribuição e Alocação de Tarefas

De acordo com a definição apresentada, um sistema multiagente é composto de diversos agentes que trabalham de forma cooperativa para realizar determinada tarefa ou atingir determinado objetivo. Sendo assim podemos dizer que, na execução de tal tarefa, cada agente possui atribuições individuais que juntas culminarão na resolução do problema. Estas atribuições ou podem ser executadas de forma mais ou menos eficiente por determinados agentes dependendo das características ou estado dos mesmos, por isso é necessário que estas tarefas sejam distribuídas da forma mais otimizada e conveniente possível.

A distribuição ou alocação de tarefas é então nada mais que o processo de atribuição de determinado problema, para ser resolvido por determinado agente. Esta atribuição pode ser fixa ou dinâmica, sendo o último o caso mais interessante, pois permite ao sistema distribuir os problemas conforme a disponibilidade dos agentes e das características dos agentes disponíveis.

O protocolo CNP (Contract Net Protocol) proposto em (DAVIS; SMITH, 1983) é um dos mais conhecidos e mais utilizados e utiliza um conceito de economia de mercado para a distribuição de tarefas. Inúmeras extensões e adaptações do CNP foram apresentadas desde então, algumas delas como as discutidas em (WALSH; WELLMAN, 1998) e (GERKEY; MATARIC, 2002) estendem o protocolo de forma a torna-lo distribuído, outras como a extensão proposta em (AKNINE et al, 2004) introduzem paralelismo e tolerância a falhas ao sistema.

- **2.4 Redes e Conectividade**

Redes de comunicação podem ser representadas, de um ponto de vista simplificado, por grafos nos quais as interfaces de comunicação configuram os vértices e os enlaces entre estas configuram as arestas pelas quais trafegam as mensagens. Aplicando sobre esta representação os conceitos de teoria dos grafos pode-se estender a definição de grafo conexo, aquele no qual existe um caminho que conecta quaisquer dois pontos, para o contexto de redes definindo-se então uma rede conexa como uma rede na qual quaisquer duas interfaces de comunicação consigam enviar com sucesso mensagens uma para a outra.

Redes de comunicação podem estar configuradas em diversos tipos de topologia, ou seja, voltando a representação em formato de grafo, a distribuição espacial dos nodos e das arestas que os ligam podem ser muito diversificadas. Estas diferentes topologias permitem à rede diferentes características: as topologias em estrela possuem um nodo comutador central pelo qual passam todas as mensagens da rede; já as topologias em anel configuram normalmente redes com graus maiores de redundância, pois se perdermos um enlace a rede ainda continua conexa. Uma topologia importante e cada vez mais utilizada, principalmente devido ao crescimento e popularização das redes sem fio, é a topologia do tipo malha, nesta não existe um a lei de formação, normalmente cada nodo conecta-se ao maior número de nodos possível, configurando assim múltiplas rotas de encaminhamento de mensagem e aumentando a redundância da rede.

- 2.4.1 Redes sem fio

Nas últimas décadas redes de comunicação sem fio têm se tornado extremamente populares, seu conceito é simples: utilizar o ar como meio físico para o transporte de informação através de onde eletromagnéticas. Esta teoria, apesar de simples, apresenta desafios aos engenheiros encarregados na construção de interfaces que a utilizem pois, ao contrário do meio tradicional, cabos, sinais eletromagnéticos no ar estão sujeitos à grandes níveis de ruído, perda e dispersão tornando a preocupação com a qualidade do sinal cada vez mais importante.

Para medir a qualidade dos sinais recebidos por determinado receptor definiu-se então, na indústria, uma métrica conhecido como RSSI ou Indicador de Intensidade do Sinal Recebido. Esta métrica consiste basicamente em uma medida do valor da potência do sinal recebido por determinada interface receptora.

- **3. Definição do Problema**

O principal objetivo a ser alcançado no decorrer deste projeto é a elaboração de um algoritmo distribuído de coordenação de movimento que permita a manutenção de uma rede de comunicação confiável formada por VANT's e que permita paralelamente a execução de missões específicas de variada natureza por estes veículos. Neste contexto a natureza das missões foi definida em termos de duas tarefas básicas: o patrulhamento e cobertura de determinado perímetro a ser definido pelo controle de missão; e, encontrado ou conhecido um ponto de interesse (POI) dentro deste perímetro realizar o tratamento deste ou alocar um agente para tanto.

Considerando que o sistema possui, em situações normais, um número finito e limitado de agentes (VANT's) este problema começa a tornar-se complexo e pouco trivial. Nestas condições não basta ao algoritmo apenas a coordenação do posicionamento espacial dos agentes para realizar o patrulhamento, a manutenção da conectividade e evitar colisões entre eles; mas também a alocação de um subconjunto destes mesmos agentes para tratamento dos pontos de interesse. Esta pluralidade de tarefas a serem exercidas pelo sistema pode vir a tornar-se ainda mais complexa se, em algum cenário, os agentes forem diversificados e possuírem, entre si, recursos diversificados, como por exemplo diferentes tipos de câmeras e ou sensores específicos para o tratamento de certos alvos, requisitando a alocação de agentes específicos em momentos específicos.

Outro problema a ser considerado nesta análise é o compromisso existente entre a eficiência dos algoritmos de cobertura de perímetro e a conectividade da rede. Uma vez que a movimentação dos nodos pode acarretar sua desconexão e que a conectividade da rede depende das características dos módulos de comunicação utilizados e de sua distribuição espacial é impossível garantir, dependendo das características da área a ser patrulhada, que ambos, manutenção da conectividade e patrulhamento sejam realizados de forma plenamente satisfatória.

É provável ainda que em certas situações seja impossível o processamento e reorganização do sistema de forma a cumprir plenamente todas as suas atribuições em tempo computacional satisfatório. Nestas situações será necessária então, alguma heurística, definida pelo controle de missão ou intrínseca ao sistema que permita escolher qual tarefa priorizar, tratamento de pontos de interesse, patrulhamento ou manutenção da conectividade da rede.

- **4. Trabalhos relacionados**

Em (ZLOT et al., 2002) é estudada e apresentada uma proposta de economia de mercado para alocação de tarefas entre diversos agentes, no caso robôs terrestres. A proposta baseia-se na alocação de alvos a serem visitados por cada robô. Cada alvo é leiloado utilizando heurísticas sobre o posicionamento espacial dos robôs e sobre a área mapeada de forma a garantir que os robôs realizem a cobertura mais eficiente possível de seu perímetro alvo.

Em (WALSH; WELLMAN, 1998) os autores apresentam um protocolo distribuído de economia de mercado para alocação de tarefas e recursos escasso entre agentes. Esta solução é especialmente interessante pois pode garantir a boa execução dos leilões na ausência de um agente centralizador.

Ainda com a mesma ideia (GERKEY; MATARIC, 2002) propõem outro protocolo distribuído de economia de mercado, chamado MURDOCH. O protocolo foi desenvolvido com o intuito de evitar gargalos e pontos únicos de falha em sistemas distribuídos e ambientes dinâmicos, principalmente aqueles que envolvem robôs sujeitos a falhas e mal funcionamento.

No estudo (PARUNAK; BRUECKNER; SAUTER, 2005) é apresentado o conceito biológico de feromônios (marcadores biológicos) e sua utilização em problemas de controle e coordenação de robôs e veículos não tripulados. Neste contexto os marcadores biológicos são tratados como agentes geradores de campos potenciais, atrativos ou repulsivos, que podem regem o movimento dos agentes nestes ambientes.

(SAUTER et al., 2005) estuda o desempenho e eficiência de sistemas de ferômonios em aplicações de vigilância, aquisição de alvos, e rastreamento. O sistema apresentado é testado em diversos tipos de aplicação e cenários e mostra-se eficiente em comparação a outros métodos ao mesmo tempo que não demanda ajustes complexos para otimização.

No trabalho (HAACKE, 2015) é discutido o problema de coordenação de VANT’s do ponto de vista de tratamento de pontos de interesse e cobertura de perímetro. Duas estratégias são apresentadas para a solução: a utilização de economias de mercado, e o conceito de ferômonios digitais. Estas soluções são testadas e comparadas estatisticamente levando em consideração seu desempenho na execução dos problemas propostos.

Em (ORFANUS; ELIASSEN; FREITAS, 2014) é discutida a utilização de algoritmos de coordenação de movimento aleatórios em redes de comunicação auto organizáveis para dar suporte a redes de sensores sem fio (WSN). Neste contexto são propostos e analisados algoritmos proativos e reativos de manutenção da conexão entre os nodos comutadores móveis que visam garantir a conectividade da rede ao mesmo tempo que permitem mobilidade a estes nodos.

- **5. Proposição de Soluções**

Para resolver o problema exposto no contexto deste projeto a ideia é utilizar uma abordagem mista baseada em dois tipos de algoritmos: economias de mercado e mapas de ferômonios abordados sob a óptica de campos potenciais. A primeira técnica permite a delegação do sistema de tarefas aos agentes do sistema, mais especificamente será utilizada para delegar o tratamento de determinado ponto de interesse (POI) à determinado VANT; já a segunda técnica será utilizada no tratamento dos problemas de manutenção de conectividade e cobertura e patrulhamento de perímetro.

- **5.1 Sistemas de Economia de Mercado**

Sistemas baseados em economias de mercado são normalmente utilizados com o intuito de distribuir ou alocar tarefas ou recursos em sistemas multi-agentes e inspiram-se no funcionamento de um mercado de leilões. Ao identificar uma tarefa que pode ser delegada a algum de seus agentes o sistema, através de um agente leiloeiro, inicia um leilão para definir quem a receberá. Os agentes do sistema, enquanto o leilão está aberto, podem dar lances baseados em suas habilidades ou em alguma heurística pré-definida e tentar ganha-lo, o agente que der o melhor lance recebe a reponsabilidade de executar a tarefa leiloada.

No contexto do problema abordado por este projeto o recurso principal a ser leiloado são os pontos de interesse a serem visitados pelos VANTS, desta forma, ao encontrar um POI o agente responsável por sua descoberta comunicará aos outros e um leilão será iniciado para definir qual dos veículos será deslocado para tratá-lo. É importante observar que os lances são baseados em heurísticas, tais como a distância de determinado agente ao POI, custo de movimentação até o POI, estado atual do agente e também habilidades dos VANT, que podem ser diferentes dependendo do tipo de equipamento que possuírem.

- **5.2 Modelos Potenciais e Mapas de Feromônios**

Algoritmos de Mapas de Feromônios e do tipo Colônia de Formigas são algoritmos de otimização biologicamente inspirados. A ideia central é, mimetizando o realizado por algumas espécies de insetos, de que os agentes sejam capazes de depositar e sentir marcadores em determinado ambiente compartilhado. Estes marcadores permitem orientar os outros agentes do grupo na tomada de decisões sobre as ações futuras, gerando assim uma certa coordenação de grupo altamente satisfatória para suas necessidades. No caso dos insetos os marcadores são substâncias químico-biológicas chamadas feromônios.

Conforme visto em (PARUNAK; BRUECKNER; SAUTER, 2005) algoritmos deste tipo podem ser abordados sob uma ótica de campos potenciais de forma a reger a movimentação espacial dos indivíduos móveis de um sistema. Nessa abordagem cada ponto do espaço possui determinado vetor associado que indica o gradiente do campo potencial gerado pelos depósitos de marcadores já realizados no ambiente. Os agentes podem, baseando-se na orientação deste gradiente, escolher a melhor direção para movimentar-se de forma a encontrar um ponto de equilíbrio neste campo potencial.

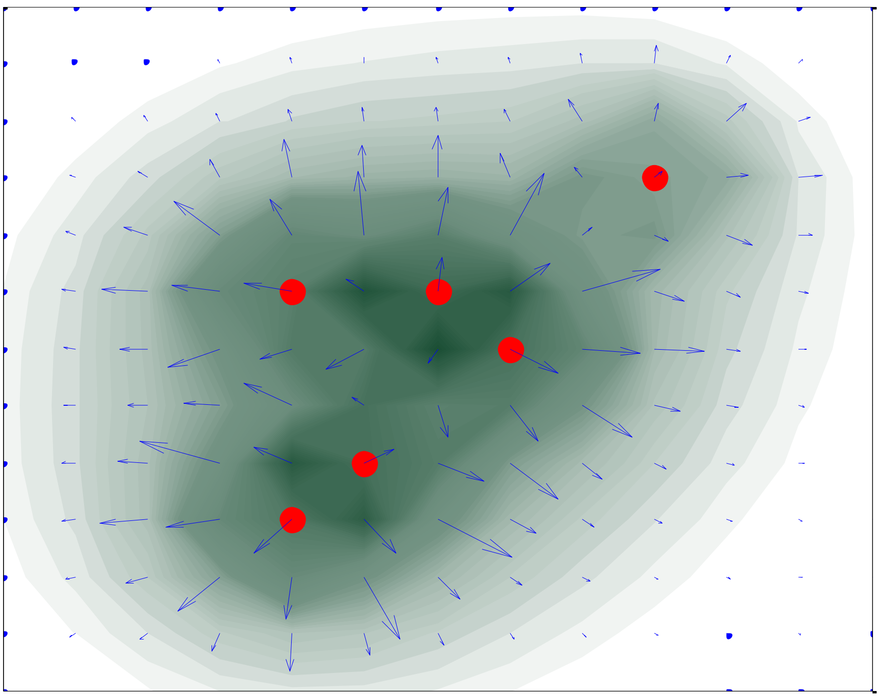


Figura 1. Representação de um campo potencial e de seu gradiente gerado pela deposição de marcadores repulsivos

No contexto proposto a ideia é fazer com que os agentes do sistema, no caso os VANT's baseiem-se no conceito de marcadores e campos potenciais para comunicar aos demais informações relativas ao cumprimento das missões e à manutenção da rede. A cada ciclo de processamento os marcadores que rodeiam os agentes são sentidos e uma nova decisão é tomada utilizando-os como base. Assim, efetuando a deposição de marcadores atrativos ou repulsivos determinado VANT pode comunicar a necessidade de aproximação de outros agentes para garantir conexão ou informar aos demais que determinadas áreas do perímetro já foram visitadas, aumentando a cobertura de novas áreas. No algoritmo proposto o campo potencial gerado por determinado marcador em um ponto do ambiente será caracterizado utilizando três características principais na seguinte relação:

- O campo será inversamente proporcional ao quadrado da distância do referido ponto ao local de deposição do marcador;
- O campo será diretamente proporcional à intensidade da capacidade repulsiva ou atrativa do marcador;
- O campo será inversamente proporcional ao tempo decorrido desde a deposição do marcador;

A combinação destes três fatores leva a uma solução satisfatória para todos os fatores de dificuldade encontrados na delimitação do problema de coordenação do movimento dos VANT's. Podemos observar na Figura 1 o efeito da deposição de marcadores repulsivos (representados pelos círculos escuros) na forma de uma representação da intensidade do campo gerado por eles e dos vetores gradiente que o caracterizam.

- 5.2.1 Mapas de Feromônios no Problema de Patrulhamento de Perímetro

Para a resolução dos problemas de patrulhamento o algoritmo age de maneira bastante simples. Cada VANT possuirá armazenado em sua memória uma representação do perímetro total a ser monitorado. Nesta representação a área total será dividida em forma diversos pequenos setores de área menor do que a mínima coberta pelo sensor de um dos VANT's ao sobrevoar determinado local, desta forma podemos garantir que todos os setores serão cobertos de forma satisfatória.

Ao visitar determinado setor um agente comunicará aos demais a deposição de um marcador repulsivo naquele local, os demais, por sua vez, atualizarão seu mapa de setores registrando a deposição e, ao calcular sua próxima direção de movimento, serão guiados pela força repulsiva da deposição para longe deste setor, possivelmente para um setor ainda não visitado. Para evitar que setores próximos àqueles que já foram visitados não o sejam ou que determinada área fique muito tempo sem cobertura será utilizada a proporcionalidade temporal do campo, ou seja, quanto mais tempo decorrido desde a deposição de marcador em determinado ponto, mais fraco o campo gerado por este será, de forma que, ao fim de determinado período de tempo, sua intensidade seja tão baixa que os agentes serão levados a visitá-lo de novo, ou a, ao menos aproximar-se dele.

Neste cenário um parâmetro importante a ser considerado é a quantidade de setores utilizada no cálculo da força potencial incidente sobre determinado VANT, calculá-la utilizando todos os setores do mapa pode resultar em um esforço computacional muito grande, no entanto analisar apenas os setores imediatamente subjacentes àquele em que o agente se encontra pode resultar em comportamentos inadequados. Este parâmetro deverá, portanto, ser bem definido e estudado através de testes e simulações de forma a garantir que o sistema funcione de forma correta.

- 5.2.2 Mapas de Feromônios no Problema de Manutenção da Conectividade

Para garantir a conectividade da rede e fazer com que, na maior parte do tempo, todos os agentes encontrem-se conectados a ideia é utilizar os campos potenciais de forma a manter os agentes em posição de equilíbrio espacial em relação ao grupo do ponto de vista de qualidade do sinal. Cada VANT terá então a capacidade de depositar em si próprio e nos outros marcadores virtuais.

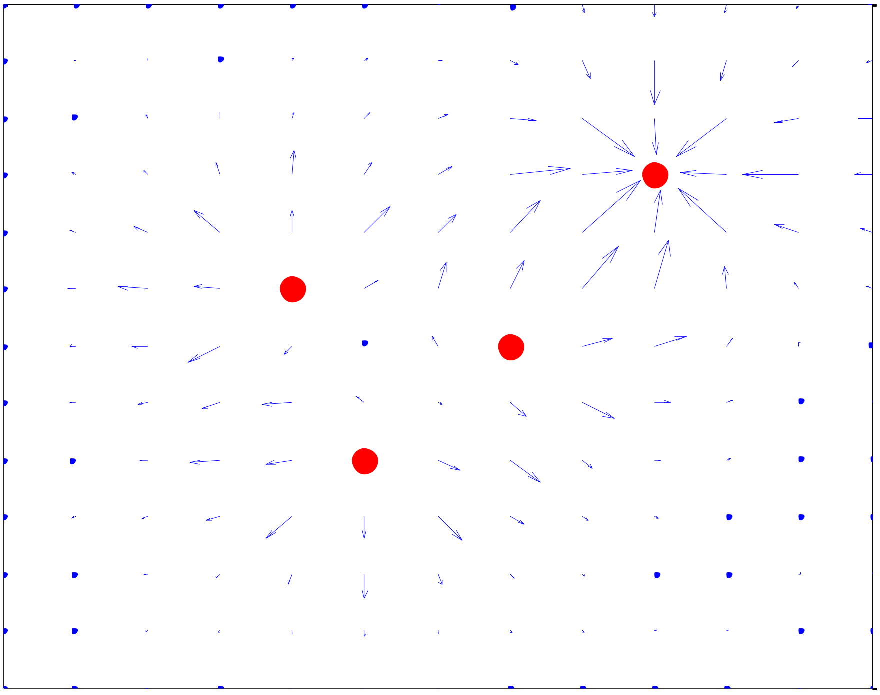
A proposta é fazer com que cada agente seja gerador de um campo repulsivo ou atrativo ajustado com base na a intensidade do sinal recebido por aqueles diretamente conectados a ele, mais especificamente os parâmetros de RSSI. Utilizando este parâmetro é possível ajustar a forma com que o campo gerado pelos demais agentes contribuirá no cálculo da força potencial incidente sobre determinado VANT de forma a mantê-lo não muito aproximado dos agentes conectados a ele de forma a comprometer as missões de tratamento de alvos ou patrulhamento, mas também não muito afastado de forma a desconectar-se da rede.

Como, neste caso, a capacidade repulsiva ou atrativa de cada VANT é variável e configurável pode-se, por exemplo, fazer com que determinado agente marque-se de forma bastante atrativa, chamando assim os outros a aproximarem-se dele para melhorar a qualidade conexão, ou com que se marque de forma repulsiva fazendo com que os demais se afastem. Esta característica dinâmica da capacidade de geração de campo dos agentes pode ser utilizada também com o intuito de gerenciar os compromissos do sistema, como por exemplo movimentação a lugares distantes sem a desconexão da rede ou manutenção da conexão e patrulhamento simultâneos.

- 5.2.3 Mapas de Feromônios no Problema de Deslocamento para Tratamento de POI's

Para resolver o problema de tratamento de POI's, após feito o leilão dos pontos de interesse, o algoritmo propõe a associação de uma força atrativa de grande magnitude ao POI desejado (Figura 2). Sempre é interessante lembrar que cada VANT ou agente do sistema possui sua própria representação interna do mapa de marcadores, de forma que um mesmo ponto ou agente possa ser gerador de diferentes campos, cada um visto da ótica de um agente diferente

Associando um potencial atrativo a determinado POI sob o ponto de vista de determinado agente dele encarregado o algoritmo estará influenciando este agente a aproximar-se deste ponto. A escolha da magnitude deste potencial é um fator importante a ser estudado, pois o ideal é que este não seja alto o suficiente de forma a levar o agente a desconectar-se da rede sem que esta tenho tempo de organizar-se de forma a reconecta-lo em tempo hábil ou de manter sua conexão.



que o observa. **Figura 2. Representação do gradiente de potencial gerado pela deposição de três marcadores repulsivos e de um marcador atrativo de alta magnitude**

- **6. Planejamento do TG2**

A seguir apresenta-se o planejamento da segunda etapa deste trabalho, a ser realizado durante o TG2. Basicamente este planejamento é composto de 6 fases principais: Projeto e Implementação da Solução; Teste em Ambiente Simulado; Validação do Algoritmo; Implantação e teste em VANT's Reais; Análise dos resultados obtidos; e Conclusão de Escrita e Apresentação do Trabalho.

- **6.1 Implementação da Solução**

O principal objetivo desta fase é o projeto e implementação dos algoritmos propostos nesta etapa do trabalho. Uma das tarefas principais desta fase será o estudo dos parâmetros varáveis do algoritmo de campos potenciais e a influência de sua variação no comportamento do sistema e nos padrões de movimentação dos VANT's.

Previsão de Conclusão: agosto/2015

- **6.2 Teste em Ambiente Simulado**

Nesta fase será desenvolvido um ambiente simulado de testes que seja capaz de representar através de modelos satisfatórios os fatores ambientais que podem influenciar no comportamento do sistema, como por exemplo a perda de potência do sinal dos módulos sem fio durante sua propagação ou eventuais níveis de ruídos que possam interferir na comunicação. Uma vez pronto o simulador o algoritmo será submetido a diversos teste neste ambiente de forma a verificar seu bom funcionamento e se este atinge os requisitos de comportamento necessários.

Previsão de Conclusão: Setembro/2015

- **6.3 Validação do Algoritmo**

Tomando como base os resultados dos experimentos simulados será feita a validação do algoritmo e de seu bom funcionamento para futuras implantações. É nessa fase também que está prevista a correção de eventuais comportamentos indesejados no sistema.

Previsão de Conclusão: Setembro/2015

- **6.4 Implantação e teste em VANT's Reais**

O projeto no qual este trabalho insere-se possui recursos destinados à aquisição dos componentes e plataformas físicos reais necessárias para o teste do algoritmo proposto. Desta forma, uma vez validado existe a previsão de realizar a implantação do algoritmo em um VANT real e testar seu funcionamento. A plataforma a ser utilizada ainda depende de decisões de projeto, mas estas encaminham-se, até o momento, para a utilização de rádios Xbee Digimesh 900Mhz acoplados à computadores Raspeberry Pi montados sobre um VANT.

Previsão de Conclusão: outubro/2015

- **6.5 Análise dos resultados obtidos**

Nesta fase será realizada a análise crítica dos resultados obtidos no trabalho, serão também estudadas as dificuldades encontradas durante sua realização bem como apresentadas propostas de trabalhos futuros que podem ser realizados sobre este algoritmo.

Previsão de Conclusão: novembro/2015

- **6.6 Conclusão de Escrita e Apresentação do Trabalho.**

O planejamento reserva esta fase para a conclusão da escrita da monografia a ser entregue ao fim do TG2. Este documento resumirá as investigações realizadas, as técnicas utilizadas, as dificuldades encontradas e os resultados obtidos. Será também, nesta mesma fase que ocorrerá a aprestnação à banca avaliadora.

Previsão de Conclusão: dezembro/2015

- **7. Conclusão**

Esta etapa do trabalho consistiu na apresentação dos desafios e conceitos envolvidos na proposição de uma solução ao problema de desenvolver um algoritmo de coordenação para um grupo de Veículos Aéreos Não-Tripulados. Durante o decorrer deste artigo os problemas propostos foram delimitados e discutidos do ponto de vista de sistemas multi-agentes e planejamento distribuído, trazendo conceitos desta área da computação como enfoque principal. Ao fim do estudo foi proposta uma solução para o problema composta de uma abordagem mista composta de sistemas baseados em economias de mercado e em algoritmos de mapas de feromônios e campos potenciais. Esta solução foi então debatida de forma a estabelecer características que permitissem a ela resolver de forma satisfatória o problema proposto.

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