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Canadian Arctic sovereignty: Local intervention by flocking UAVs

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Defence R&D Canada – Ottawa

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Local intervention by flocking UAVs

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Abstract

The importance of local intervention capability for the assertion of Canadian Sovereignty in the Northwest passage is recognized. However, Canada presently lacks the ability to deploy at any northern position, on demand, assets that could search a wide area for rescue or surveillance purposes. This fact motivated the exploration we report here on the feasibility of a rapid intervention system based on a carrier-scouts design according to which a number of unmanned aerial vehicles (UAVs) would be transported, air launched and recovered by a larger carrier aircraft.

A 1973 report produced by the Tactical Combat Aircraft Programs of the Boeing Aerospace Company for the US Air Force [16] and the 2007 thesis of A. Chalamont [5] lead to the conclusion that the airborne launch and recovery of many UAVs from a single carrier aircraft is feasible and requires only already existing technology. In the present report, we propose a solution to the remaining problem of managing simultaneously the many UAVs that are required by the vastness of the areas to be surveyed, with a minimum number of human controllers and communications. Namely, we present algorithms for the self-organization of the deployed UAVs in the formation patterns that they would use for the tasks at hand. These would include surveillance operations during which detailed photographic or video images would be acquired of activities in a region of interest, and searching an area for persons, vehicles or ships in distress and providing a visual presence for such. Our conclusion is that the local intervention system with flocking UAVs that we propose is feasible and would provide a very valuable asset for asserting and maintaining Canadian Sovereignty in the North.

Résumé

L’importance de disposer d’une capacité d’intervention locale permettant d’affirmer la souveraineté canadienne dans le secteur du passage du Nord-Ouest est reconnue. Toutefois, le Canada n’est actuellement pas en mesure de déployer ses ressources à volonté dans le Nord afin d’effectuer des missions de sauvetage ou de surveillance sur de vastes zones. Cette réalité a justifié les recherches dont nous faisons rapport ici sur la faisabilité de créer un système d’intervention rapide basé sur le concept d’aéronef transporteur-observateur. Ce concept repose sur l’utilisation d’un certain nombre de véhicules aériens sans pilote (UAV) qui seraient transportés, largués en vol et récupérés par un aéronef lanceur de plus grande taille.

Un rapport datant de 1973 produit par les programmes de l’avion de combat tactique de l’entreprise Boeing Aerospace pour la US Air Force [16] et la thèse de 2007 de M. A. Chalamont [5] ont permis de conclure que le lancement et la récupération en vol de nombreux UAV est possible en utilisant un seul aéronef lanceur. Un tel système ferait appel à des technologies qui existent déjà. Dans le présent rapport, nous proposons une solution au problème restant, c’est-à-dire la gestion simultanée du grand nombre d’UAV nécessaire pour couvrir l’immense étendue des secteurs à surveiller avec un nombre minimal de contrôleurs humains et de transmissions. En fait, nous présentons des algorithmes qui permettraient aux UAV déployés de gérer de façon autonome l’organisation des formations de vol utilisés en fonction des tâches à effectuer. Ces tâches comprendraient notamment les opérations de surveillance qui nécessitent la prise d’images photographiques ou de vidéos détaillés des activités ayant cours dans la région d’intérêt, et la recherche dans un secteur de personnes, de véhicules ou de navires en détresse et assurer une présence visuelle dans de tels cas. Notre conclusion est qu’il est possible de mettre sur pied le système d’intervention local que nous proposons — qui fait appel à de nombreux UAV — et que

ce système constituerait un atout précieux qui permettrait d'affirmer et de maintenir la souveraineté canadienne dans le Nord.

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Executive summary

Canadian Arctic sovereignty:

Gilles Labonté; DRDC Ottawa CR 2009-243; Defence R&D Canada – Ottawa; January 2010.

Introduction or background: The importance of local intervention capability for the assertion of Canadian Sovereignty in the Northwest passage is recognized. However, Canada presently lacks the ability to deploy at any northern position, on demand, assets that could search a wide area for rescue or surveillance purposes. This fact motivated the exploration we report here on the feasibility of a rapid intervention system based on a carrier-scouts design according to which a number of unmanned aerial vehicles (UAVs) would be transported, air launched and recovered by a larger carrier aircraft.

A 1973 report produced by the Tactical Combat Aircraft Programs of the Boeing Aerospace Company for the US Air Force [16] and the 2007 thesis of A. Chalamont [5] lead to the conclusion that the airborne launch and recovery of many UAVs from a single carrier aircraft is feasible and requires only already existing technology.

Results: In the present report, we propose a solution to the remaining problem of managing simultaneously the many UAVs that are required by the vastness of the areas to be surveyed, with a minimum number of human controllers and communications. Namely, we present algorithms for the self-organization of the deployed UAVs in the formation patterns that they would use for the tasks at hand. These would include surveillance operations during which detailed photographic or video images would be acquired of activities in a region of interest, and

searching an area for persons, vehicles or ships in distress and providing a visual presence for such.

Significance: Our conclusion is that the local intervention system with flocking UAVs that we propose is feasible and would provide a very valuable asset for asserting and maintaining Canadian Sovereignty in the North.

Future plans: Future work would include extension of these algorithms to include more realistic models of vehicle dynamics and more elaborate collision avoidance algorithms.

Sommaire

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Gilles Labonté; DRDC Ottawa CR 2009-243; R & D pour la défense Canada – Ottawa; Janvier 2010.

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Résultats: Dans le présent rapport, nous proposons une solution au problème restant, c'est-à-dire la gestion simultanée du grand nombre d'UAV nécessaire pour couvrir l'immense étendue des secteurs à surveiller avec un nombre minimal de contrôleurs humains et de transmissions. En fait, nous présentons des algorithmes qui permettraient aux UAV déployés de gérer de façon autonome l'organisation des formations de vol utilisés en fonction des tâches à effectuer. Ces tâches comprendraient notamment les opérations de surveillance qui nécessitent la prise d'images

photographiques ou de vidéos détaillés des activités ayant cours dans la région d'intérêt, et la recherche dans un secteur de personnes, de véhicules ou de navires en détresse et assurer une présence visuelle dans de tels cas.

Importance: Notre conclusion est qu'il est possible de mettre sur pied le système d'intervention local que nous proposons — qui fait appel à de nombreux UAV — et que ce système constituerait un atout précieux qui permettrait d'affirmer et de maintenir la souveraineté canadienne dans le Nord.

Perspectives: Les recherches futures pourraient porter sur l'extension de ces algorithmes afin qu'ils comprennent des modèles plus réalistes de la dynamique des véhicules et sur des algorithmes de prévention de collisions plus élaborés.

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1 Introduction

The introduction to the report "Canadian Arctic Sovereignty" by M. Carnaghan and A. Goody [4] provides the motivation for the present study. This report states the following.

"The Arctic region has featured prominently in debates about Canadian sovereignty. There has been a renewed focus on the Arctic due to the effects of climate change in the region, notably the melting of the polar ice caps. At the same time, there are continuing strategic issues relating to potential incursions into Canadian Arctic territory at various levels – airspace, surface (terrestrial and maritime), and sub-surface (by nuclear submarines). Canada's ability to detect and monitor such territorial incursions and to enforce sovereign claims over its Arctic territory in such cases has been questioned.

Other countries, including the United States, Russia, Denmark, Japan, and Norway, as well as the European Union, have expressed increasing interest in the region and differing claims in relation to international law. In particular, many observers believe that the Northwest Passage, the shipping route through Canada's Arctic waters, will be open to increased shipping activity in the coming decades as the ice melts. Canada's assertion that the Northwest Passage represents internal (territorial) waters has been challenged by other countries, including the United States, which argue that these waters constitute an international strait (international waters). Interest in the region's economic potential has resulted in discussions of increased resource exploration and disputed sub-surface resources, as well as concerns over environmental degradation, control and regulation of shipping activities, and protection of northern inhabitants. It is important to note that the Arctic is a vast and remote territory that presents many difficulties in terms of surveillance, regulation, and infrastructure development."

The authors of this report also point out that it is urgent that Canada supports its claim by its presence in the region, by monitoring the passage and ensuring compliance with Canadian sovereign claims. Such control could also be seen as ensuring the security of the Americas' perimeter, which could make the United States more favourable to our position.

1.1 Canada's Presence in the North

The Carnaghan and Goody [4] report recalls that the Canadian Government has had serious considerations of establishing a presence in the north through purchasing nuclear submarines and ice-breakers. We quote from this report the following list of assets that presently establish Canada's presence in the Arctic.

- The Canadian Coast Guard operates a fleet of five icebreakers that guide foreign vessels through Canada’s Arctic waters and assist in harbour breakouts, routing, and northern re-supply. The Canadian Navy does not currently have the capacity to operate within the Arctic ice.

- The Canadian Forces Northern Area (CFNA) is headquartered in Yellowknife. CFNA headquarters comprises 65 Regular Force, Reserve, and civilian personnel. CFNA military activities per year include two “Sovereignty Operations (Army),” two “Northern Patrols” (flights of Aurora patrol aircraft), 10-30 “Sovereignty Patrols” (CFNA), and one “Enhanced Sovereignty Patrol.” As part of the Canadian Forces Transformation, CFNA will assume a greater command and control function. CFNA will become the “Northern” regional headquarters of the new Canada Command in 2006.

- As part of the North American Aerospace Defense Command (NORAD), Canada maintains a chain of unmanned radar sites, the North Warning System (NWS). The NWS provides limited aerospace surveillance of Canadian and United States Arctic territory.

- Canada's Department of National Defence created Project Polar Epsilon, which "will provide all-weather, day/night [surface] observation of Canada's Arctic region," using information from Canada's RADARSAT 2 satellite, by May 2009. RADARSAT-2 is a commercial satellite that carries a Synthetic Aperture Radar (SAR) to produce images of the surface of the earth. It was launched in December, 2007 on a Soyuz vehicle from Kazakhstan. RADARSAT-2 is the result of a collaboration between - the Canadian Space Agency (CSA) and MacDonald, Dettwiler and Associates Ltd. (MDA). MDA is responsible for the operations of the satellite and the ground segment. The CSA supplies RADARSAT-2 data to Canadian government agencies. The satellite's altitude is 798 km. Its spatial resolution is from 3 to 100 m depending on the SAR beam mode used. It can sweep a 500 km wide area and covers the region north of 70^0 latitude every day.

1.2 Problem Statement

Canada must be able to monitor the activities and provide search and rescue services in the Northwest Passage. RADARSAT-2 provides high altitude images of the area but there remains the need to be able to intervene locally for the purpose of closer surveillance or search and rescue. These interventions have to be provided in a timely manner. If surveillance is involved, the possible offenders should not have the time to organize and conceal their doings. If it is search and rescue, the victims should obviously be found as soon as possible before they suffer more damages. Given the vastness of the region, an effective local intervention system must have the ability to deploy many assets so that large areas are effectively covered at the same time.

1.3 Proposed Solution

We propose that one or more UAV carrier aircrafts be put on stand-by at some permanent stations in the north so that they can be dispatched promptly to any given position. These aircrafts would carry in their hull a number of UAVs. They would bring these UAVs close to the site of the required intervention, and launch them in mid-air, at an appropriate altitude. Once deployed, these would self-organize in a formation appropriate for the task at hand. They would either scan the region in search for a target or fly about a given target location. Their carrier aircraft would remain in the vicinity of the UAVs if it is required to collect the data transmitted by them. Otherwise, it could go away and come back to recover the UAV when their mission is accomplished. Once their mission is accomplished, the UAVs would be recovered in mid-air by their carrier aircraft, which would then return to its base.

In the following sections, we shall examine the feasibility of the crucial manoeuvres required for this system to work. For now, we list some of the advantages self-organization of the UAVs would provide.

1.4 Advantages of Self-Organization of the UAVs

- Having a formation of ten or more UAVs flying at the same time, in close formations, would require at least the same number of expert pilots and entail considerable logistic problems. Thus, the ability of the UAVs to self-organize in formations decreases considerably the human resources that would otherwise be required in the carrier aircraft or on the ground.

- The self-organization control algorithms we propose use only local information that is obtainable by individual UAVs. No communications are even required between UAVs; they only need to be able to determine their relative positions with respect to their neighbors. Thus self-organization leaves free all the available communication channels for the UAVs to transmit data, be it video or other, to the carrier aircraft.

- The proposed system is endowed with considerable robustness by the fact that all the UAVs have the same role. Their control algorithm is such that the loss of one or more members of the formation will not prevent the task from being accomplished. The fleet of UAVs cannot be rendered inoperative or disabled due to the loss of a leader; it has no leader.

1.5 System Paradigm

The concept of marsupial robots, that is of a system composed of a large robot that carries an assembly of smaller robots that it deploys as appropriate, is not new. It is described by R.R. Murphy [15], and by G.A. Bekey [2] as the "Ranger-Scout Architecture".

In order to apply this concept to UAVs, it is necessary to devise a method for the small UAVs to be launched safely by their carrier aircraft and be later recovered by it. The method we propose is based on two studies that we will briefly summarize below. The first one is a 1973 report that the Tactical Combat Aircraft Programs of the Boeing Aerospace Company produced for the US Air Force [16] and the second one is the 2007 MSc thesis of A. Chalamont [5]. Furthermore, there has to be a control algorithm that will make the UAVs self-organize in the appropriate formation for searching or accompanying a target. We will describe such an algorithm below.

2 Airborne Launch and Recovery System

We now review briefly the conclusions of the above mentioned two studies about the air-borne launch and recovery system.

2.1 The Boeing Fighter-Carrier Study

In 1973, the Tactical Combat Aircraft Programs of the Boeing Aerospace Company produced a report for the US Air Force on the feasibility of a micro-fighter design such that a number of such vehicles could be transported internally, air launched and recovered, by a carrier aircraft. The carrier considered was a Boeing 747 class aircraft with micro-fighters of weights of about 4,500 kg, wing-span of 5.5 m and length of 9m [16]. Such a system was considered interesting for its offering a valuable capability of rapid deployment of multi-purpose strike assets. It would have allowed for intercontinental response, with large combat forces, before an aggressor could fully mobilize its forces. The scope of investigation included an evaluation of various fighter and carrier aircraft concepts, and an assessment of various launch and recovery schemes and technology applications.

Their carrier design included:

- Dual launch and recovery bays.
- In-Flight refuelling booms for initial contact and refuel.
- High speed air launch and recovery.
- Carrier versatility to operate in alternate roles, such as cargo carrier, troop carrier or tanker.

Figure 1 shows schematically the carrier with its micro-fighters. The fighters are recovered by making contact with the refuelling boom. Retracting action of the telescopic boom would then pull the fighter into an appropriate structure into which it would be locked in place. Its engine would then be shut down and it would be hoisted into the launch and recovery bay of the carrier. The mechanism would then move the fighter to an overhead traveler support for hangar stowage.

Deployment of this system was investigated for various scenarios in Europe, the Middle East, Indian Ocean and CONUS Air Defence. It was determined that the micro-fighters could be deployed in 1/10 the time with 1/3 the manpower required for a current Composite Air Strike Force (CASF) squadron. The study concluded that strike fighters operating from airborne aircraft carriers is technically feasible. It was determined that the modifications of an existing aircraft to make it into the carrier would not be too difficult: 1975 technology already existed for the carrier loading, on-board handling and operational analysis of the baseline system. This fighter-carrier system ended up not being produced to be replaced by a fleet of very fast long-range fighter aircrafts.

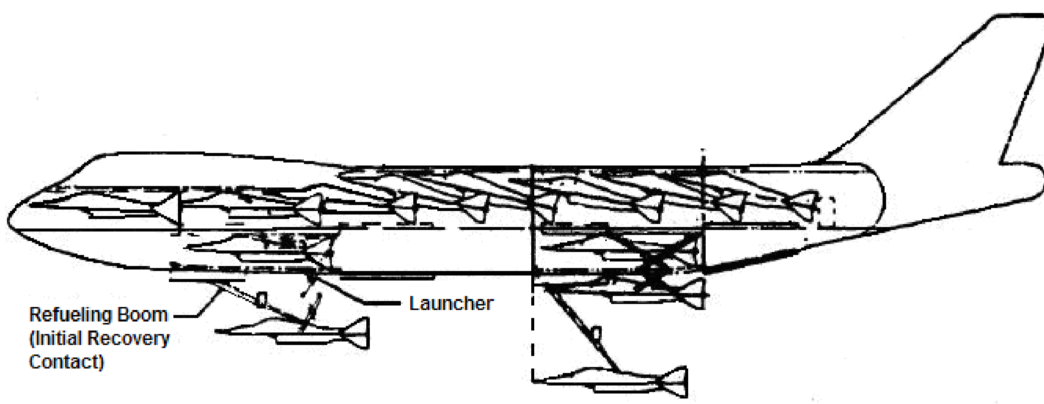


Figure 1: Micro-Fighters Airborne Carrier in the Boeing report [16].

2.2 The Chalamont UAV-Capture Study

In his 2007 MSc thesis, A. Chalamont [5] investigated in details the feasibility of airborne launch and recovery of a UAV from a carrier aircraft. His proposed method for retrieving the UAV also uses a modified refuelling boom. The UAV would be captured by it and then pulled in by the cable, to be attached to the carrier aircraft. A few US patents have been filed for various capture and attachment systems, one of them, proposed by R.G. Harrison [7], consists precisely in a modified refuelling capture device, which would hold firmly the UAV and pull it to the carrier, as shown in Figure 2. These capturing systems are obviously simple variations of the system proposed in the Boeing study of 1973 mentioned above.

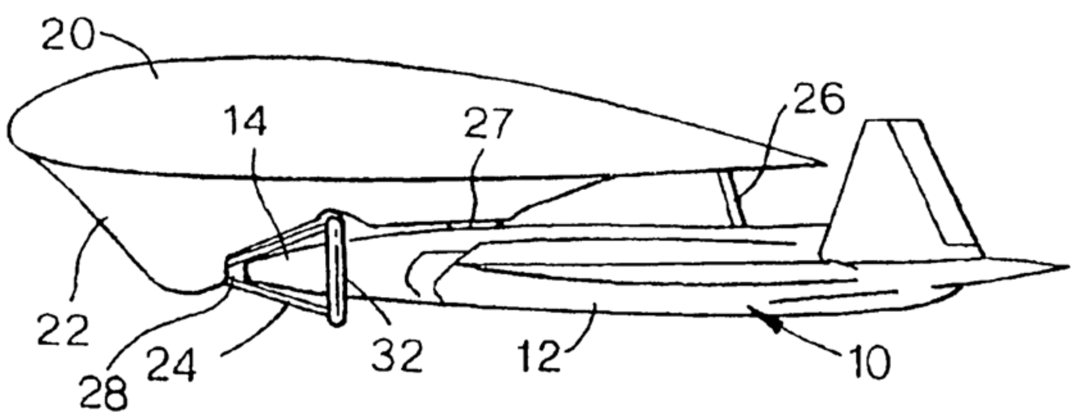


Figure 2: UAV attached under the wing of a carrier aircraft by a modified refuelling capture device in the patent of R.G. Harrison [7].

Chalamont recognizes as crucial the following topics:

- the determination of the UAV configuration needed to be captured,

- the evaluation of the ability of the UAV to reach the capture devise,
- the study of the aerodynamic coupling between the UAV and the carrier aircraft during the launch and recovery,
- the cable and towed body dynamics.

The coupling between the carrier aircrafts and the smaller aircraft is essentially the same one that exists during airborne refuelling manoeuvres. It is therefore rather well understood in the case of UAVs that would be approximately of the size of fighter aircrafts. Wind tunnel tests determined that it was also possible to control the position of a much smaller towed UAV in spite of the vortices produced in the wake of the larger carrier aircraft. Chalamont developed control algorithms and conducted recovery tests for a Jindivik UAV, using the state space representation of Lancaster [11]. The Jindivik was designed by the Australian Government Aircraft Factories in 1952 and it has been used by Australian RAE and British RAF as a weapons target. The characteristics of the Jindivik Mk 4 used in his study are the following ones: maximum take-off weight of 1655 kg, wing span of 6.32 m and length of 7.11 m. The tests conducted by Chalamont indicated that this UAV can be effectively controlled for its retrieval by the carrier.

The conclusion of his thesis is that the feasibility of the airborne launch and recovery of a UAV by a carrier aircraft can be considered as very likely. There does not appear to be any major problem that would make the operation unmanageable.

2.3 Alternate Airborne UAV Retrieval System

An alternative to the cable-drogue UAV capture system, for UAVs that would be small enough, could consist in using a net that would be deployed by the carrier aircraft. Net capture systems are already in use for some UAVs, as for example the 3-meter wide, 14 kg, Raytheon's KillerBee [9], shown in Figure 3, and he much larger 5.2-meter, 204 kg Pioneer used by the US Navy [10], shown in Figure 4. Such systems should be easily adapted for the retrieving of UAVs by the carrier aircraft. An appropriate rigid frame could hold the net in place under the carrier aircraft in order to catch the UAV. The carrier would approach the UAV from behind, and more or less match its velocity with that of the UAV so as to minimize its impact into the net. The engines of the UAV would be shut down and it would be pulled into the launch and recovery bay of the carrier. Humans would then untangle the UAV from the net and place it in an appropriate stowage.

Figure 3: The Raytheon's KillerBee being retrieved with a net [9].

Figure 4: The Pioneer UAV being retrieved with a net [10].

2.4 Feasibility of UAV Airborne Launch and Recovery

Upon combining together the results of the two studies mentioned in Section 4.1 and 4.2, one can conclude that a system for the airborne deployment and retrieval of many UAVs by a carrier aircraft is feasible. Indeed, the Chalamont study shows how to capture UAVs from another aircraft and the Boeing report provides the mode of operation for the deployment and retrieval by the carrier aircraft once the UAV is captured. When more than one UAV is involved, the manoeuvre would simply be repeated until all UAVs have been similarly processed.

There are many UAVs on the market that would be adequate for this system. One that has gathered considerable interest is the Aerosonde that is famous for having been the first UAV to cross the Atlantic. It costs approximately $70,000 and is produced by Aerosonde Ltd, which has recently been acquired by the AAI Corporation. The official website that provides information on the Aerosonde is [8]. This UAV was designed as a general purpose, very versatile, aircraft and it has already been tested in taxing conditions such as in hurricane studies [14] and in the Arctic [13] . Its characteristics are:

Length: 1.74 m	**Wingspan**: 2.9 m
Empty weight: 13 kg	**Gross Weight**: 15 kg
Cruise speed: 80-120 km/h	**Maximum speed**: 150 km/h
Endurance: 30 h	**Range**: 3,000 km
Service ceiling: 4,500m	

In the Boeing study, the micro-fighters were considered to have a weight of about 4,500 kg, a wing-span of 5.5 m and a length of 9 m [16]. In the Chalamont thesis [5], the UAV's weight was 1,655 kg, it wing span 6.32 m and its length of 7.11 m. These aircrafts are considerably bigger than the Aerosonde. Thus, the carrier aircraft could be much smaller than the Boeing 747 class aircraft proposed in the Boeing report.

Furthermore, if such smaller aircrafts as the Aerosonde were used, it may be possible to modify the refuelling-capture device, proposed by Boeing and Chalamont, so that the whole UAV could fit inside it, thus simplifying appreciably the retrieval phase.

Eventually, the carrier aircraft could also be a UAV but initially, because of the numerous manipulations of the carried UAVs, it would have to be manned.

3 On Formations

Once the UAVs have been deployed in an area of interest, they would have to self-organize in a pattern that renders their task more efficient. The basic two formations we consider here are those that would be used for surveillance operations during which detailed photographic or video images are acquired of activities in a region of interest, and for searching an area for persons, vehicles or ships in distress and providing a visual presence for such. In the first formation, the UAVs self-organize in a straight line that makes a prescribed angle with their common direction of flight, at a constant altitude, where they are placed at the same distance from each other. Figure 5 shows this formation. In this figure, the UAVs are represented by small triangles, the vector $\mathbf{v}_0$ corresponds their common velocity. Each UAV, except the first one of the line, has a neighbor situated at position $\mathbf{d}$ with respect to itself. This formation is a one-sided version of that used by migrating birds. In the second formation, shown in Figure 6, the UAVs are moving in a circle about the target, at the same distance from each other, at a specified altitude h_0 and at the same speed. For M UAVs moving on a circle with radius R_0, with center C_0 at altitude h_0, the angle between two neighboring UAVs is $\Delta\theta = 2\pi/M$, and the length of the arc of circle between them is $R_0\ \Delta\theta$. Any one of these two formations would be appropriate for the efficient pick-up of the UAVs by the carrier aircraft.

Snow Geese
http://animalphotos.info/a/2008/08/26/
snow-geese-flock-flying-in-v-formation/

F-16 Formation
Photo by Tom Reynolds / Photo archive DOD
on Internet

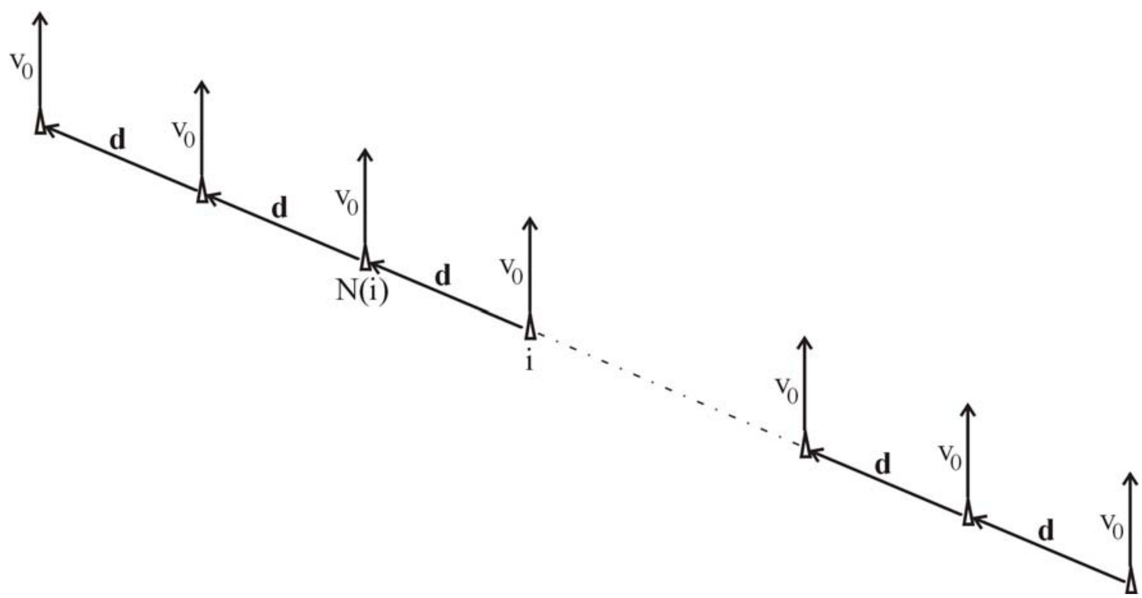
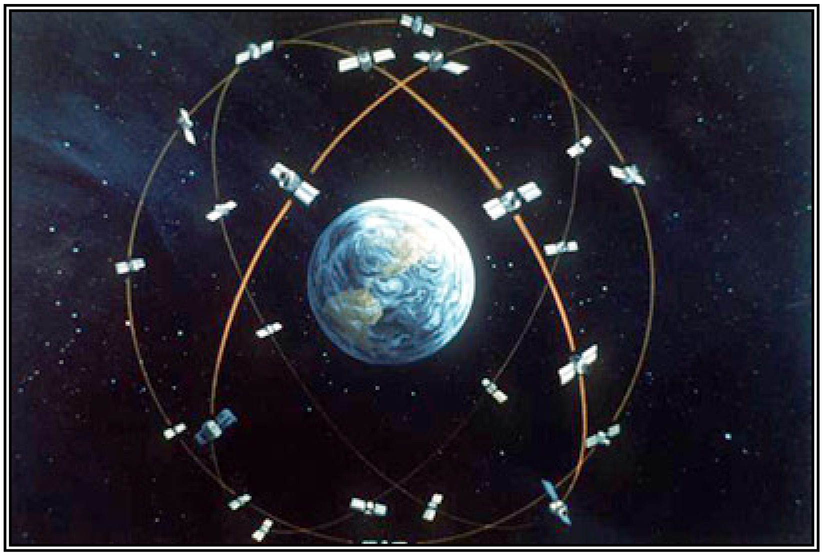


Figure 5: Straight line flight formation seen from above.



GPS Satellites
http://www.cira.colostate.edu/cira/RAMM//hillger/GPS.htm

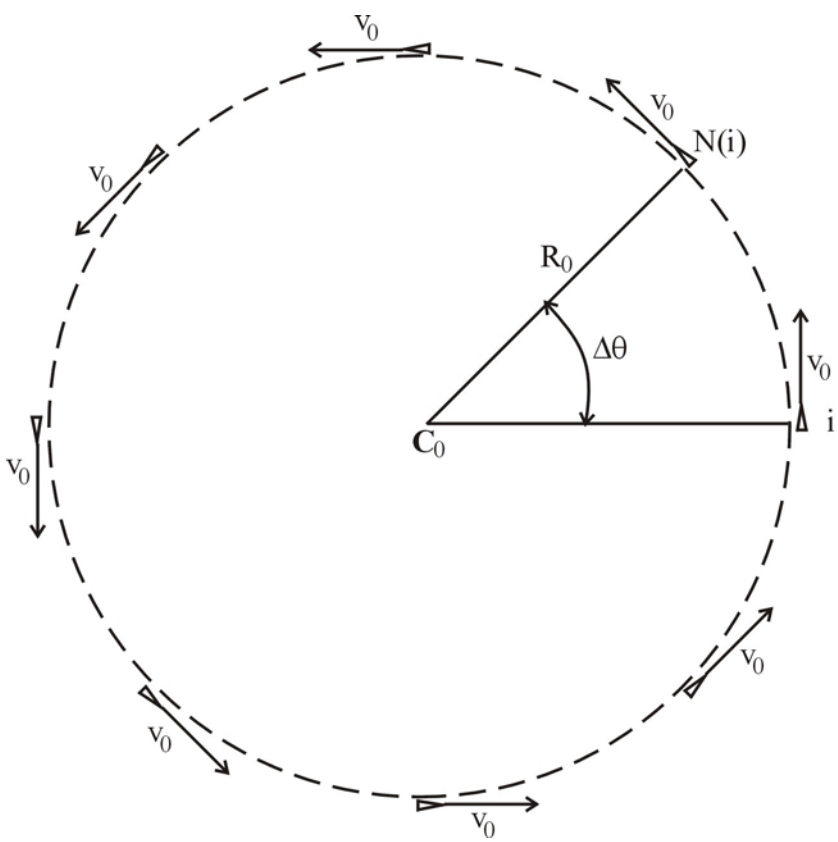


Figure 6: Circular flight formation with 8 UAVs seen from above.

3.1 On Flocking Algorithms

By far, the best source of information on self-organized flocking is the web page of C.W. Reynolds, who is the pioneer of research in this domain, at http://www.red3d.com/cwr/boids/ and his paper [22]. Some partial reviews of flocking algorithms can also be found in Parunak [20] and Bamberger [1]. The two principal approaches that involve self-organization are the consensus approach, around which are centered the works described by C. W. Reynolds [22] , L. Fang and P.J. Antsaklis [6], and R. Olfati-Saber [17, 18, 19] and the stigmergic approach, which is well represented in the works of H. V. D. Parunak [20, 21], and S.A. Brueckner [3]. We recall that according to Reynolds, individual agents do not pay attention to all of the other agents in the flock; they use only local perceptions of the flock. The "amount of thinking" an agent has to do is independent of the number of agents in the flock. He states the following rules, which have to be applied in this order of precedence, to obtain flocking:

1. Avoid collisions with nearby flock-mates.
2. Attempt to match velocity with nearby flock-mates.
3. Attempt to stay close to nearby flock-mates: move toward their average position.

The algorithms we use hereafter are variations of that of Reynolds that we have modified to deal with formations instead of swarms. We recall that formations differ from swarms in that they are gatherings of agents that form a particular pre-selected pattern.

4 Inter-agent Force Field Approach

We are here mainly interested in the underlying mechanisms of flocking, which are actually independent of internal shape changes and articulation of the agents. Thus, we will consider, as is customary to do (see Reynolds [22]), that the dynamics of the UAVs is that of point masses. It is only when actual flight controllers for the UAVs have to be built that appropriate UAV equations of motion will have to be used. At that point, only the navigational component of the force will differ from the values given here. Our study follows somewhat the approach presented by Reynolds [22] and Olfati-Saber [17,18,19].

We consider a system of M identical UAVs that are artificially numbered from 1 to M. It is important to note that this numbering will not play any role in the organization of the flock; it is only introduced in order to be able to describe the algorithms quantitatively. The position of the i-th UAV is represented by its coordinate vector $\mathbf{x}_i$ and its velocity by the vector $\mathbf{v}_i$. Each UAV's dynamics are ruled by the same equations of motion, namely

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i \qquad \text{and} \qquad \frac{d\mathbf{v}_i}{dt} = \mathbf{u}_i \tag{4.1}$$

where $\mathbf{u}_i$ is the force (rigorously speaking, it is the force divided by the mass) acting on the i-th UAV.

As in Olfati-Saber [17, 18, 19], the force term in Eq. (4.1) is divided into two terms as

$$\mathbf{u}_i = \mathbf{u}_i^F + \mathbf{u}_i^N \tag{4.2}$$

in which $\mathbf{u}_i^F$ is the α-lattice forming force and $\mathbf{u}_i^N$ is the navigational feedback force. The first force is one that is exerted between the i-th UAV and its neighbors while the second force does not concern the other UAVs; it is internal to the i-th UAV. It is produced by its own controller to rule its dynamics. We note that it will generally be preferable to take this navigational force to be stronger than the pattern shaping one, so that the UAV will already be flying in the right direction when they start organizing their position with respect to each other. Otherwise, there could be pointless switching places between UAVs while they are trying to reach their prescribed flying direction. This principle is in accordance with the formation of flying patterns in migrating birds; firstly, they start moving toward their destination, then they will meet other birds moving more or less in the same direction and place themselves in a specific position relative to these other birds.

In his work, Olfati-Saber takes the force $\mathbf{u}_i^F$ to be composed of two terms: one term is an inter-agent force that is repulsive at short distances to ensure the avoidance of inter-agent collisions, and the other term is a consensus forcing term that causes the alignment of the velocities of neighboring UAV. In our case, the force $\mathbf{u}_i^F$ will also comprise two terms; the first one will also be an inter-agent force but, as we will see in our examples below, the second one will often be different in nature than that used by Olfati-Saber.

4.1 Inter-Agent Force Field

Reynolds [22] uses two different collision avoidance mechanisms. One is based on the force field concept and the other one on discrete "steer-to-avoid" decisions. According to the force field mechanism, a virtual repulsion force is generated by the obstacles that will divert the approaching agents. This method works well in most situations but fails in some. For example, if an agent approaches an obstacle in a perpendicular direction to it, then the force will slow it down to zero velocity and accelerate it backwards. This is definitely an inappropriate motion when the agent should simply move sideways and avoid the obstacle. A controlled steer-to-avoid manoeuvre is a better method for collision avoidance in such a situation. Thus, we will use a repulsive force field except for head-on or near head-on collisions, in which steer-to-avoid will take over. Agents must also attract each other. This can be easily realized by letting the inter-agent force have a long term attractive component.

Examples of forces that have the required properties are that which exists between molecules and is derived from the Lennard-Jones potential [12], combinations of Coulomb forces, a force proposed by Olfati-Saber [18], and the force derived from the following potential. This latter force has the advantage of being very simple to compute while presenting all the desired properties. The potential we will consider is:

$$V^c(r) = \begin{cases} \dfrac{aA}{2}\left[1-\dfrac{r}{a}\right]^2 & \text{when } 0 \le r \le b \\ B(r-a) & \text{when } b < r \end{cases} \tag{4.3}$$

in which A and B are non-negative constants that are the amplitudes of the repulsive and the attractive components of the force respectively. "a" is the radius at which the force changes from repulsive to attractive, and $b = a\left[1+\dfrac{B}{A}\right]$ is the point of transition from the quadratic to the linear form of the potential. This point is such that the force resulting from this potential is continuous. The gradient of this potential yields a force that is directed from the position of the agent to the origin, and that has the intensity:

$$F^c(r) = \begin{cases} A\left[1 - \dfrac{r}{a}\right] & \text{when } 0 \le r \le b \\ -B & \text{when } b < r \end{cases} \tag{4.4}$$

V^c and F^c are shown in Figure 7. As this figure shows, the potential described in Eq. (4.3) is actually very similar to a truncated Coulomb potential.

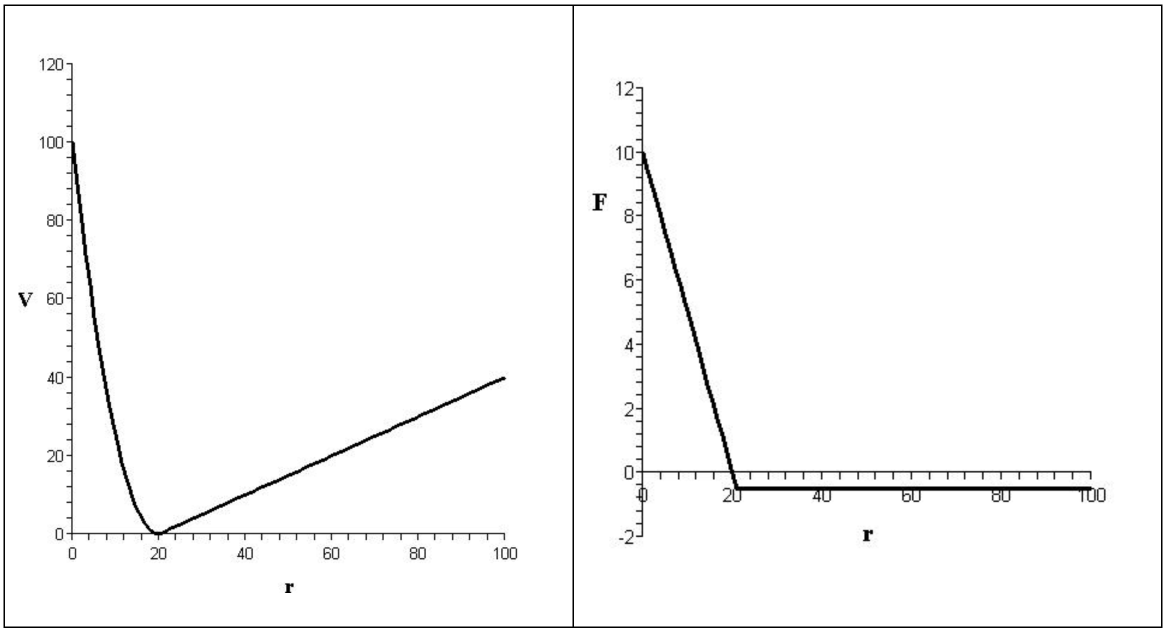


Figure 7: On the left-hand-side: a simple potential that ensures agent collision avoidance and attraction at long distances. On the right-hand-side: the magnitude of the corresponding force.

Since each agent in the swarm is surrounded by this inter-agent force field, each agent is subjected to the resultant of all the forces produced by all the other agents. Thus, the force acting on the i-th agent is:

$$\mathbf{F}_i^c = \sum_{j \in \overline{S}(i)} \mathbf{F}^c(\mathbf{x}_i, \mathbf{x}_j) \tag{4.5}$$

in which $\overline{S}(i)$ represents the whole swarm except for the i-th agent itself, and

$$\mathbf{F}^c(\mathbf{x}_i, \mathbf{x}_j) = F^c(\| \mathbf{x}_i - \mathbf{x}_j \|) \frac{(\mathbf{x}_i - \mathbf{x}_j)}{\| \mathbf{x}_i - \mathbf{x}_j \|} \tag{4.6}$$

If a force with a finite range of "r_a" is required, then the form of the above potential could be taken to hold until r reaches a certain point c that is between b and r_a, at which point it would become $\frac{b}{(r_a - c)}(r - r_a)$ until $r = r_a$. It would then remain constant. The corresponding force would then start increasing linearly from its value of -B at r = c, until it reaches the value of 0 at $r = r_a$ where it would remain.

4.2 Collision Avoidance Test

Since an important function of the inter-UAV force is to prevent them from colliding, it is crucial that we test whether the force we will use does produce that effect. A simple such test consists in seeing whether two UAVs will avoid a collision when they are sent toward each other, flying at the same altitude, with opposite velocities in a direction that is almost head-on. Figure 8 shows the trajectory that these two UAVs follow. As can be seen, when they are close enough to feel the repulsive force produced by the other UAV, they start moving away from it until they are enough to prevent the collision. They then come back to pursuing their initial trajectories. This being the behavior that is desired, we shall then use that particular force in all our experiments on formation and swarm self-organization.

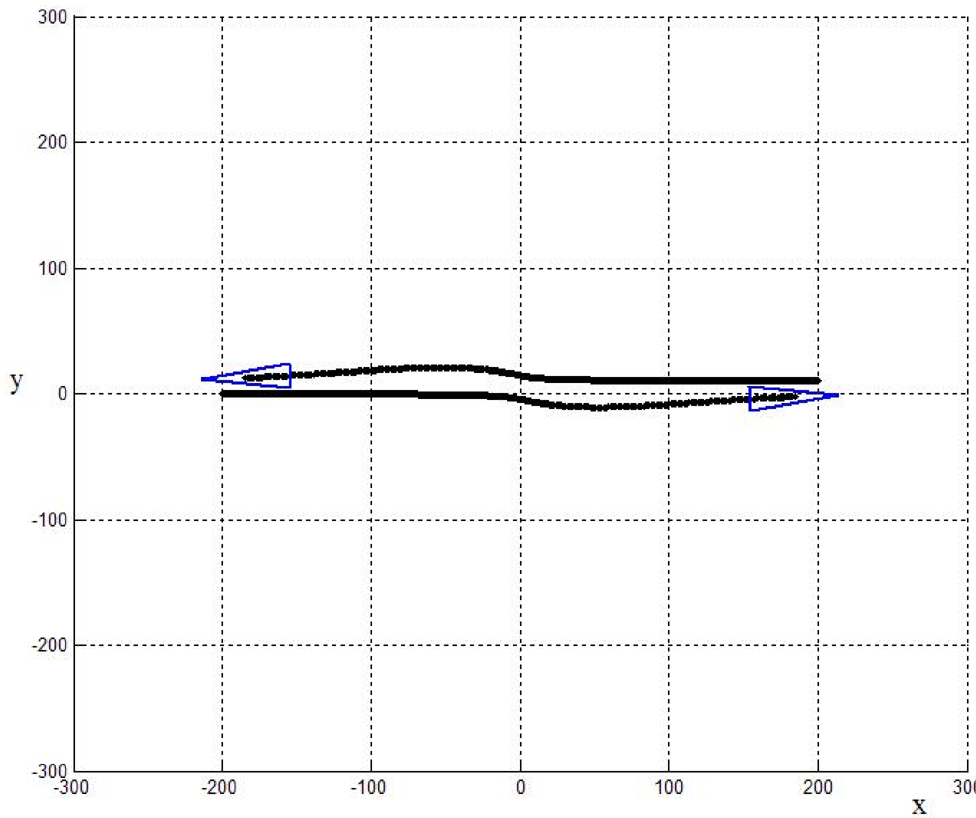


Figure 8: Trajectories of two UAVs that avoid a head-on collision.

5 Straight Line Formation Algorithm

In order to obtain a straight line formation, characterized by the translation vector **d** (see Figure 5), we define the neighborhood N(i) of the i-th UAV to contain the index of the closest UAV that is in the closed half-space **E**(i) defined as

$$\mathbf{E}(i) = \{\mathbf{x} \mid \mathbf{d} \cdot (\mathbf{x} - \mathbf{x}_i) \geq 0\} \qquad (5.1)$$

We recall that the set of points $\{ \mathbf{x} \mid \mathbf{d} \cdot (\mathbf{x} - \mathbf{x}_i) = 0\}$ constitute a plane that contains the point $\mathbf{x}_i$ and for which the vector **d** is a normal. All the points **x** that satisfy the inequality $\mathbf{d} \cdot (\mathbf{x} - \mathbf{x}_i) > 0$ are on the side of that plane towards which the vector **d** points. We note that N(i) is a dynamic neighborhood as it may well happen that the neighbor of the i-th UAV change as the flock is forming. In particular it could happen that N(i) is empty because there are no UAVs in the region of space **E**(i).

For this formation, we take the second term of the force $\mathbf{u}_i^F$ to be a force exerted on the i-th UAV as:

$$\mathbf{F}_d(\mathbf{x}_i, \mathbf{x}_{N(i)}) = c_d \begin{cases} (\mathbf{x}_{N(i)} - \mathbf{x}_i - \mathbf{d}) & \text{if N(i) is not empty} \\ [0, 0, 0]^T & \text{if N(i) is empty} \end{cases} \qquad (5.2)$$

The navigational control force $\mathbf{u}_i^N$ is the force that the auto-pilot will generate in order for the UAV to follow its course. For this formation, each UAV will be told to fly at a specific altitude h_0 while moving with the velocity $\mathbf{v}_0$. Therefore, we take the navigational force to be simply

$$\mathbf{u}_i^N = c_h (h_0 - z_i)\, \mathbf{k} + c_v (\mathbf{v}_0 - \mathbf{v}_i) \qquad (5.3)$$

in which c_h and c_v are positive constants, z_i is the altitude component of the position vector $\mathbf{x}_i$, and $\mathbf{k}$ is the unit vector along the positive z-axis, which is here the local axis pointing up, i.e. in the direction opposite to that of the gravitational force.

We note that the information that the UAVs require is only locally available information. For computing its flocking force, an UAV needs to measure its relative position with respect to its neighboring UAVs within the distance "a", so as to compute the collision avoidance force according to Eqs.(4.4) and (4.6). It also needs to measure its relative position with respect to its nearest neighbor in the half-space E(i), defined in Eq.(5.1). The other parameters required are those used for navigation purposes. They are its altitude and its velocity.

5.1 Straight Line Formation Test

Figure 9 shows the evolution of a flock when fifteen UAVs that start with position vectors with random components in the interval [-100, 100], and with velocities v that have random x and y components in the interval v_0 [-1 , 1] and random z-component in the interval v_0[-0.1, 0.1]. We note that there is no particular reason for taking these particular intervals and the algorithm works just as well for any other initial conditions. The time scales of the simulation is not meaningful as the UAV represented do not obey aircraft equations of motion, and behave simply as point masses. The pictures of the flock shown in Figure 9 are separated by time intervals of the same length. This figure shows clearly the efficient formation of the pattern by the flock of UAVs.

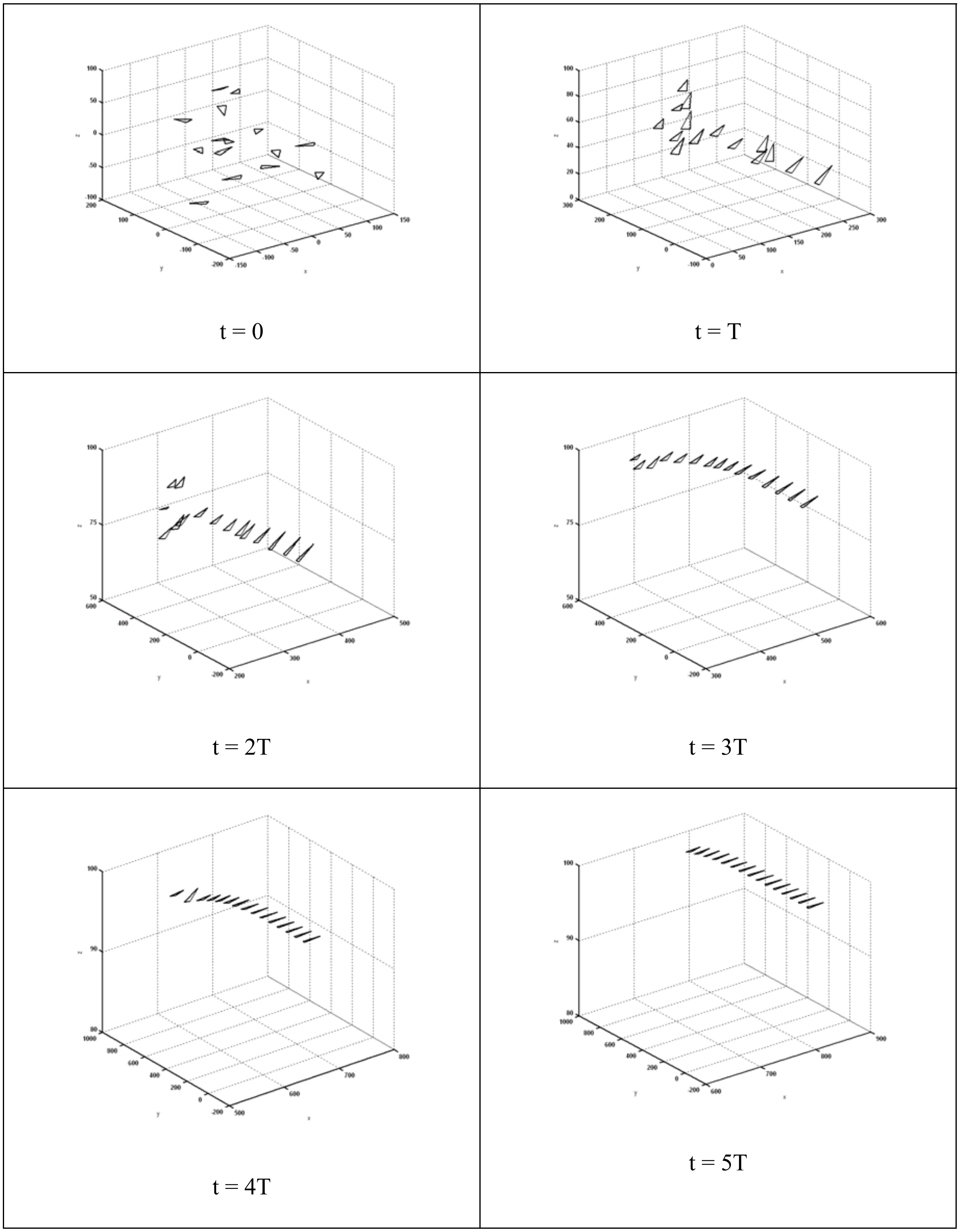


Figure 9: Evolution of a flock of fifteen UAVs from random positions to a straight line formation. The number below the pictures represent the instants of times, T being arbitrary.

6 Circular Formation Algorithm

In order to obtain a circular formation of radius R_0, at a fixed altitude h_0, as shown in Figure 6, we consider the neighborhood N(i) of the i-th UAV to contain the index of the nearest UAV that is in the closed half-space **E**(i) defined as

$$\mathbf{E}(i) = \{\mathbf{x} \mid \mathbf{v}_i \cdot (\mathbf{x} - \mathbf{x}_i) \geq 0\} \tag{6.1}$$

This is very similar to what we did for the linear formation except that the constant vector **d** is here replaced by the velocity vector $\mathbf{v}_i$ of the i-th particle. In this case, the set of points $\{ \mathbf{x} \mid \mathbf{v}_i \cdot (\mathbf{x} - \mathbf{x}_i) = 0\}$ constitute a plane that contains the point $\mathbf{x}_i$ and that is perpendicular to the velocity of the i-th UAV. All the points **x** that satisfy the inequality $\mathbf{v}_i \cdot (\mathbf{x} - \mathbf{x}_i) > 0$ are therefore in front of that UAV. Again, N(i) is a dynamic neighborhood because it may happen that the neighbor of the i-th UAV change as the flock is forming. N(i) is empty when there are no UAVs in front of the i-th one or in the same plane perpendicular to $\mathbf{v}_i$.

For this formation, we take the second term of the force $\mathbf{u}_i^F$ to be a force exerted on the i-th UAV as:

$$\mathbf{F}_c(\mathbf{x}_i, \mathbf{x}_{N(i)}) = c_c \begin{cases} R(\Delta\theta)\,(\mathbf{x}_{N(i)} - \mathbf{C}_0) - (\mathbf{x}_i - \mathbf{C}_0) & \text{if N(i) is not empty} \\ [0, 0, 0]^T & \text{if N(i) is empty} \end{cases} \tag{6.2}$$

in which $R(\Delta\theta)$ is the rotation matrix that transforms the vector $(\mathbf{x}_{N(i)} - \mathbf{C}_0)$ into $(\mathbf{x}_i - \mathbf{C}_0)$ when both $\mathbf{x}_i$ and $\mathbf{x}_{N(i)}$ are on the circular orbit. It is

$$R(\Delta\theta) = \begin{bmatrix} \cos(\Delta\theta) & \sin(\Delta\theta) & 0 \\ -\sin(\Delta\theta) & \cos(\Delta\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6.3)$$

The navigational control force $\mathbf{u}_i^N$ is the force that keeps the UAV on its prescribed trajectory. For this formation, each UAV will be told to fly at a specific altitude h_0 while moving with the velocity $\mathbf{v}_i$ that corresponds to a circular orbit. When an UAV is in the prescribed circular orbit with radius R_0, and speed v_0, its position can be written as

$$\mathbf{x}_i = \mathbf{C}_0 + [R_0 \cos(\omega t), R_0 \sin(\omega t), h_0]^T \quad (6.4)$$

in which $\omega = v_0/R_0$. Its velocity is therefore

$$\mathbf{v}_i = R_0\, \omega[- \sin(\omega t), \cos(\omega t), 0]^T \quad (6.5)$$

Therefore,

$$\mathbf{v}_i = \omega\, R(-\pi/2)\, (\mathbf{x}_i - \mathbf{C}_0) \quad (6.6)$$

where R is the rotation matrix defined above.

Therefore, we take the navigational force to be

$$\mathbf{u}_i^N = c_h\, (h_0 - z_i)\, \mathbf{k} + c_v \left[\frac{v_0}{R_0} R(-\pi/2)\, (\mathbf{x}_i - \mathbf{C}_0) - \mathbf{v}_i \right] + \ldots$$

$$+ c_R\, (R_0 - R_i)\, \mathbf{n}_{0i} + c_{NV}\, (V_0 - \|\mathbf{v}_i\|)\, \tilde{\mathbf{v}}_i \quad (6.7)$$

in which c_h, c_v, c_R and c_{NV} are positive constants, $R_i = \| \mathbf{x}_i - \mathbf{C}_0 \|$, $\mathbf{n}_{0i}$ is the unit vector directed from $\mathbf{C}_0$ to $\mathbf{x}_i$, and $\tilde{\mathbf{v}}_i$ is the unit vector in the direction of the velocity $\mathbf{v}_i$. As in Eq. (5.3), z_i is the third component of the position vector $\mathbf{x}_i$, and $\mathbf{k}$ is the unit vector along the positive z-axis that points in the direction opposite to the gravitational force. The first term is a force that brings the

UAV to the altitude of h_0, the second term makes the UAV turn on a circular orbit with frequency $\omega = v_0/R_0$. Since this term only determines the ratio of the velocity v_0 of the UAV to its orbiting radius R_0, at least one of the last two terms is necessary to specify v_0 and R_0. The third term ensures that the UAV remains at a distance R_0 from the point C_0, and the last term forces its speed to be v_0. Only one of these last two terms is actually needed, however, adding the other term was found to help the convergence toward the desired orbit.

As for the linear formation, only local information is required by each UAV to realize this formation. It needs its relative position, with respect to the other UAVs within the distance "a", so as to compute the collision avoidance force according to Eqs.(4.4) and (4.6). It also needs to measure its relative position with respect to its nearest neighbor in the half-space E(i), defined in Eq.(6.1). The other parameters required are those used for navigation purposes. They are its altitude, its relative position with respect to the target, and its velocity.

6.1 Circular Formation Test

Figure 10 shows the evolution of a flock when ten UAVs that start with position vectors with random components in the interval [-50, 50], and with velocities **v** that have random components in the interval $v_0[0.1 , 1.1]$. We note that there is no particular reason for taking these particular intervals and the algorithm works just as well for any other initial conditions. The formation to obtain consists in all the UAV moving in a circular trajectory of radius $R_0 = 400$, at the altitude of $h_0 = 100$, while they are equally spaced on this circle. The time scales of the simulation is not meaningful as the UAV represented do not obey actual aircraft equations of motion, and behave simply as point masses. The pictures of the flock shown in Figure 10 are separated by time intervals of the same length. This figure shows clearly the efficient formation of the pattern by the flock of UAVs.

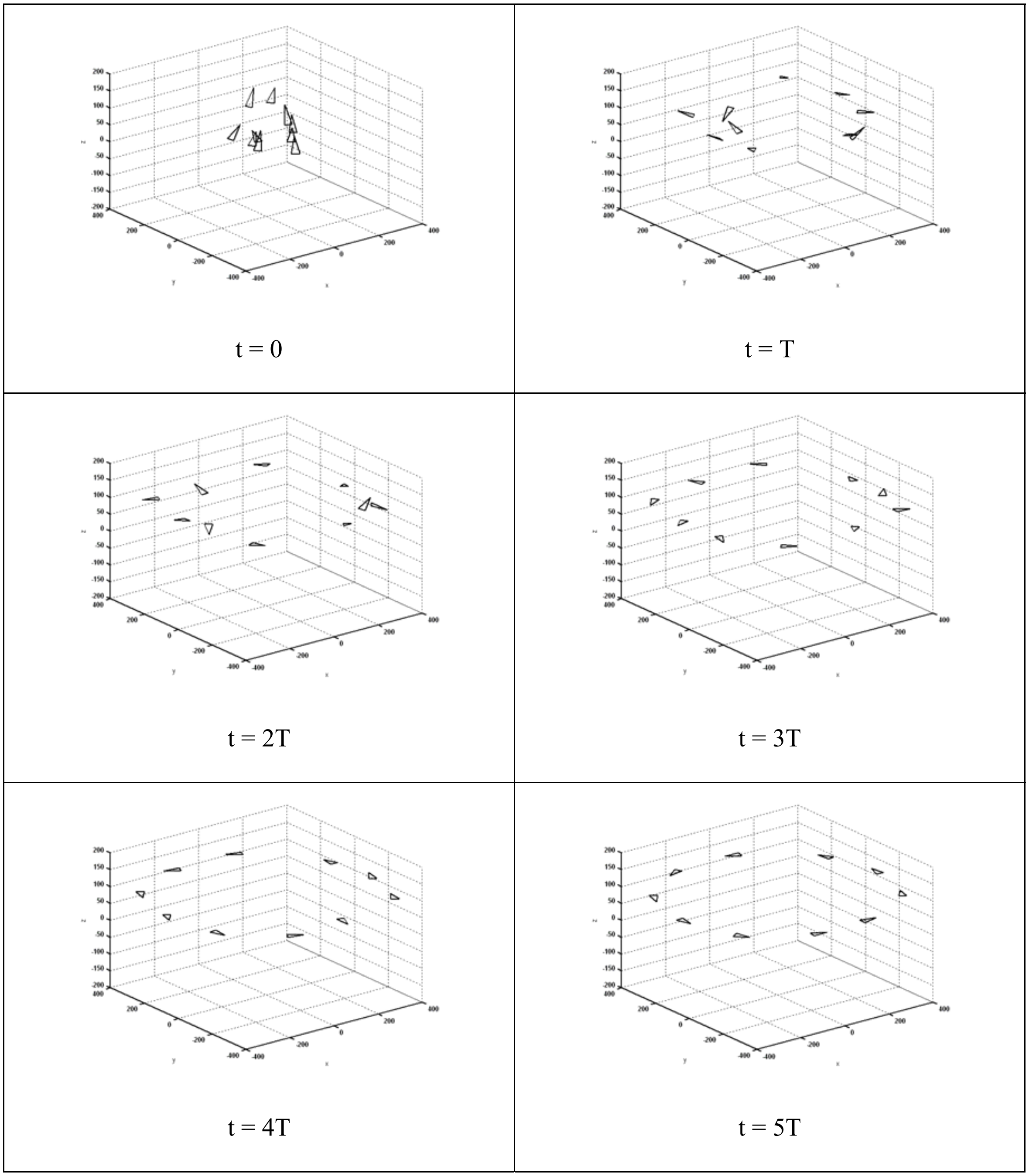


Figure 10: Evolution of a flock of ten UAVs from random positions to a circular formation. The numbers below the pictures represent the instants of times, while T is arbitrary.

7 Conclusion

The Carnaghan and Goody report on "Canadian Arctic Sovereignty" [4] provided the motivation for the present study. Thus, we reviewed briefly Canada's assets that could be used for the assertion and maintenance of its sovereignty in the north, and pointed out the need for a system that would allow the timely deployment of assets to intervene locally for the purpose of close surveillance or search and rescue. Given the vastness of the region to be surveyed, an effective local intervention system must have the ability to deploy many assets so as to cover effectively large areas at the same time.

We proposed a solution to this problem that consists in having one or more UAV carrier aircrafts on stand-by at some permanent stations in the north, from which they could be dispatched promptly to any given position. These aircrafts would carry in their hull a number of UAVs that they would bring close to the site of the required intervention, and launch in mid-air. Once deployed, these UAVs would self-organize in the appropriate formation for the task at hand: they would either scan the region in search for a target or fly about a given target location. Once their mission is accomplished, the UAVs would be recovered in mid-air by their carrier aircraft.

Given a 1973 report produced by the Tactical Combat Aircraft Programs of the Boeing Aerospace Company for the US Air Force [16] and the 2007 thesis of A. Chalamont [5], we conclude that the airborne launch and recovery of many UAVs from a single carrier aircraft is indeed feasible and requires only already existing technology. In the present report, we solve the remaining problem of devising a control strategy for the UAVs to self-organize in the appropriate patterns. This ability of the UAVs to self-organize is a necessity for this system because otherwise there would be a need for at least as many human controllers in the carrier aircraft as there are UAVs, and the communications required between the carrier and the scout UAVs would congest the available communication channels. Our flocking mechanisms use only information that is locally available to each UAV. A definite advantage provided by self-organization of the UAVs is that the resulting system is very robust to the loss of any one UAV; there are no leaders in the algorithms we propose. Scout UAVs of the Aerosonde type would be sufficient for the tasks at hand; the carrier aircraft could then be much smaller than the Boeing 747 proposed in the Boeing report [16].

We have shown that UAV controllers that make them self-organize in appropriate formations can be devised. We illustrated our formation self-organization algorithms with two basic formations that would be those used for surveillance operations and for searching an area for a target and providing a visual presence for such. In the first formation, the UAVs self-organize in a straight line that makes a prescribed angle with their common direction of flight, at a constant altitude, where they are placed at the same distance from each other. In the second formation, the UAVs move in a circle around a target, at the same distance from each other, at a specified altitude h_0 and at the same speed.

We conclude that a local intervention system consisting in a large aircraft that can carry, deploy and recover multiple UAVs that have the ability to self-organize is feasible and would provide a very valuable asset for asserting and maintaining Canadian Sovereignty in the North.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
R&D	Research & Development

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The importance of local intervention capability for the assertion of Canadian Sovereignty in the Northwest passage is recognized. However, Canada presently lacks the ability to deploy at any northern position, on demand, assets that could search a wide area for rescue or surveillance purposes. This fact motivated the exploration we report here on the feasibility of a rapid intervention system based on a carrier-scouts design according to which a number of unmanned aerial vehicles (UAVs) would be transported, air launched and recovered by a larger carrier aircraft.

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Flocking; Swarming; UAV

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