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Using drone swarms with manoeuvre units

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Summary

We have examined the use of drone swarms in support of mechanized units at low tactical level. This has primarily been done through simulations. We have used the same interface for controlling the swarm in the simulator, as we use for controlling the swarm in the real world. The drones in our swarm are small drones of less than 10 kg, with a range of no more than 10 km. We have had up to 40 drones available simultaneously in the simulator.

The purpose of our experiments have been twofold. On one hand, we want to see how a swarm can be used to assist a mechanized unit. This includes issues like what tasks the swarm could and should perform, and how a commander or battle captain best can use the information gathered by the swarm. On the other hand, we also want to improve our interface for controlling the swarm, and look at the role of the swarm operator (or operators).

It is clear that a drone swarm, or even single drones, will help increase the Situational Awareness (SA) of the platoon or company commander. Having eyes in the sky enables us to look at areas behind terrain or other obstacles without exposing units to possible enemy direct fire. A swarm increases the SA beyond that of single drones, not only because there are more sensors available, but because a swarm operates in a smarter way than a group of individual drones. Screening an area with a swarm lets you detect enemies well before they get within line of sight. Sending a swarm out in front of the unit will let you know with decent certainty whether or not the area is safe to enter, and much faster than by scouting the area on foot.

Since a swarm of small drones can cover a large area up to around 10 km away in a relatively short time, many possible targets may be detected. It is imperative that the drones have some sort of automatic detection / image recognition, as it is impossible for a drone operator to continuously watch the video stream from every drone in the swarm. Nevertheless, the operator is likely needed to verify or reject possible observations, both since hot spots in the terrain may register as a person or a vehicle, and because distinction between civilians and enemies so far is better done by an operator than a machine. In a conflict with many enemies, a swarm will detect many targets. This results in a need for means to destroy these targets, preferably without exposing own units. This can be done by various types of indirect fire, or by attack drones which may or may not be part of the swarm.

In addition to detecting enemies, SA is also about knowing where the enemy is not. A drone swarm can cover a large area relatively fast, and what area has been covered is important data, even with no detections. It is still important to note that some targets may be too well hidden to be detected, especially in dense vegetation, so an understanding of the terrain is also important.

In our experiments, few players have participated both on Blue and Red side. To better understand how a swarm best can be used in real settings and larger operations, experiments with more units, and thus more players, are needed.

The simulations have provided valuable feedback on how to improve the interface for the swarm operator. During our work, the interface has been continuously changed and enhanced. Since the same interface is used for controlling drones in the real world, these changes have also been tested during live exercises. Using experiments to improve both the interface and the way the operator works, has proven very valuable.

Sammendrag

Vi har undersøkt hvordan en dronesverm kan støtte en mekanisert avdeling på stridsteknisk nivå. Dette har vi primært gjort ved å gjennomføre simuileringer.Vi har brukt det samme brukergrensesnittet for å kontrollere svermen i simulator, som det som brukes i den virkelige verden. Dronene i våre simuleringer er små droner som veier mindre enn ti kilo, og med en rekkevidde på maksimalt ti kilometer. Vi har hatt opptil 40 droner tilgjengelig samtidig i simulatoren.

Formålet med eksperimentene har vært todelt. Vi å undersøke hovrdan en dronesverm kan brukes for å støtte en mekanisert avdeling. Dette inkluderer temaer som hvilke oppgaver svermen kan og bør gjennomføre, samt hvordan en sjef best mulig kan utnytte informasjonen innhentet av svermen. Vi ønsket i tillegg å forbedre vårt eksisterende brukergrensesnitt for kontroll av dronesverm, og se på rollen til operatøren (eller operatørene) av svermen.

Det er opplagt at en dronesverm, eller for den del individuelle droner, vil øke situasjonsforståelsen til tropps- eller eskadronssjefen. De gjør oss i stand til se områder som er bak terreng eller andre hindringer uten at man blir eksponert for direkte ild fra en eventuell fiende i området. En sverm øker situasjonsforståelsen enda mer enn enkeltdroner, ikke vare fodi man da har flere sensorer, men fordi svermen smartere enn en gruppe av individuelle droner. Ved å skjerme et område med en sverm blir man i stand til å oppdage en fiende i god tid før de får fri sikt til oss. Sender man en sverm ut for å oppklare foran avdelingen, kan du vite med brukbar sannsynlighet om et område er trygt, på betydelig kortere tid enn om man skulle oppklart området til fots.

Siden en sverm av små droner kan dekke et stort område opp til ti kilometer fra der de starter, kan det potensielt være mange mål i området. Det er avgjørende at dronene har en form for automatisk deteksjon / bildegjenkjenning, ettersom det er umulig for en operatør å kontinuerlig overvåke videoen fra hver eneste drone i svermen. Imidlertid vil operatøren trolig ha behov for å bekrefte eller avkrefte mulige observasjoner, både fordi dronene kan gi falske positive utslag, og fordi foreløpig er en menneskelig observatør bedre enn en maskin til å skille mellom faktiske fiender og sivile personer. I en konflikt med mange fiender, vil svermen trolig detektere mange mål. Dette betyr at man også kan få et behov for å ødelegge disse målene, helst uten å eksponere egne styrker. Dette kan gjøres ved forskjellige former for indirekte ild, eller ved angrep fra angrepsdroner som kan eller ikke kan være en del av svermen.

Situasjonsforståelse handler også om å vite hvor det ikke befinner seg fiender. En sverm kan dekke et stort område raskt, og det er nyttig å vite hvilke områder det har undersøkt, selv om ingenting er oppdaget der. Noen mål kan skjult for dronene, særlig i tett vegetasjon, så en forståelse av terrenget er også viktig for å anslå om området er trygt eller ikke.

Vi har hatt få spillere både på Rød og Blå side, som betyr at vi har brukt få enheter. For en bedre forståelse av hvordan en sverm bør brukes i en reell setting og i større operasjoner, vil det være nyttig med eksperimenter som involverer større avdelinger, og dermed involverer flere spillere.

Simuleringene våre har gitt oss viktig lærdom om hvordan vi kan forbedre brukergrensesnittet for svermoperatøren. Under arbeidet vårt har dette kontinuerlig blitt endret og forbedret. Ettersom dette er det samme brukergrensesnittet som brukes i den virkelige verden, har disse endringene også blitt testet under øvelser med fysiske droner. Denne måten å bruke eksperimenter for å forbedre både grensesnittet og måten operatøren jobber på, har vist seg å være svært nyttig.

Contents

1 Introduction

With drones playing an increasingly important part on the battlefield, it is important to examine how we best can use such assets - as well as what we need to do when we face such a threat ourselves. The simplest drones operate individually and are remote controlled, usually requiring one person (at least) to operate one drone. A more advanced utilization of drones involve swarms, consisting of many drones working together. This requires the drones to have some level of autonomy, in order to make it possible for one operator to control the entire swarm. What kind of autonomy is required to operate swarms of different sizes, how such swarms should be used to give the best impact on the battlefield, and how an operator best can control such swarms, are questions we address in this report.

FFIs project "Future Force" examines how unmanned systems may be used in future conflicts. FFI is also developing our own technology for using unmanned systems, which is showcased at annual experiments called LandX. See [1] for the experiment carried out in 2022, where uncrewed systems were the main focus. Among the things FFI is developing, is a drone swarm behaviour system and user interface. See [2] for a description of the Flamingo UAV. Our intention has been to support the development of this technology, and also to study how a swarm of small drones can be used to support a military unit on low tactical level.

Experimenting with drones is not always easy. There are restrictions on where and when we can operate drones, and ironically, in peace time, the restrictions are often even stronger in military areas than in civilian non-populated areas. Drones which operate with some degree of autonomy makes this even harder. Having a realistic and relevant environment for the drones to operate in is important. That means the presence of friendly and enemy units in the area, preferably conducting military operations. This requires a lot of equipment and personnel. Conducting experiments in a simulated environment rather than in the real world, we avoid these difficulties. That also allows us to test possible future functionality in and applicability of the drones, and evaluate its usefulness. This initial study of using drone swarms with manoeuvre units is done in a simulated environment, using the real drone system (Valkyrie Ground Control Station (GCS)) in conjunction with a real C2I-system (NorBMS).

Testing new technology in a simulated environment is often referred to as "synthetic prototyping" [3]. Furthermore, at FFI, multiple studies have been carried out utilizing synthetic prototyping as a means to experiment with technology [4].

There were several several reasons for conducting our experiments.

- The main goals were to be able to test the drone swarm and the drone swarm interface Valkyrie GCS in a simulated environment, to be able to make Valkyrie GCS and the drone simulator Multi-Agent Simulator (MASIM) better, and also be able to try out new functionality and improve this before trying testing it in the real world. Valkyrie GCS is the interface used both for real drones and simulated drones.
- Another goal was to showcase our simulator and setup, and demonstrate that we are able to connect it to external systems and experiment with those. We hope to do similar experiments with other systems in the future.

- Another goal was to find out how drone swarms should be operated in an "optimal" way in a battlefield, and how it would affect how other units operate. To really reach this last goal, we would need to include larger units and more players in our experiments than we have been able to thus far.

Hopefully we will be able to play larger scenarios in the future, where the drone swarm is just one element, with several units played on both Red and Blue side. That said, even with the small experiments we have conducted, we have learned some lessons about how a swarms should be operated, and some effects it is likely to have on the battlefield.

In this document we will be using both the term drone and Unmanned Aerial Vehicle (UAV) for an unmanned flying entity.

2 Drones and Swarms

There are no clear standards for drone swarms, or even what constitutes a swarm. For single drones, however, there are several categorizations (see for instance [5]). They can be categorized by factors like size, range or which operational level they support. Smaller drones generally have shorter range than large ones, and drones with longer ranges typically support higher level echelons than drones with shorter ranges, so it is really just different ways of categorizing drones by size. In addition, it is also useful to distinguish between combat drones, surveillance drones and loitering munitions. Surveillance drones do not carry weapons or warheads, only sensors. Combat drones are generally large drones that carry some sort of weapons. Loitering munitions are usually smaller drones which can can attack a target, but which are themselves destroyed in the process. Loitering munitions are sometimes referred to as suicide drones.

NATO classifies drones in three rather large categories [6]: Class I are drones with a maximum takeoff weight less than 150 kg, Class II are drones with maximum takeoff weights between 150 kg and 600 kg, and class II are drones with maximum takeoff weights over 600 kg. The class I drones consist of many very different types. While the class includes drones up to 150 kg, most class I drones used in Ukraine weigh less than 10 kg [6].

There are fixed-wing drones and drones with one or more rotors. Quad copters, drones with four rotors, are common for small drones. Fixed wing drones typically have higher speeds and longer range than quad copter drones of similar weight.

Swarms can have different types of architecture. In [7], four different types of architecture are presented: Centralized, Hierarchical, Consensus and Emergent. These are also discussed in [8]. They can roughly be described like this (see also figure 2.1):

- Centralized: Each drone in the swarm sends data to one central operator. This operator also sends orders to each drone in the swarm individually.
- Hierarchical: The drones send data to a "squad leader" drone, and this drone also distributes orders to the drones under its command. The "squad leader" then sends data to and receive orders from a higher level, and so on.
- Consensus: Every drone in the swarm communicates with every other drone in the swarm. The drones have some way, like voting, to agree on which actions they will take.
- Emergent: Individual drones react "naturally" to other drones, like in bird flocks or insect swarms.

Getting swarms to work well depends on several different technologies. This is discussed for instance in [9]. The drones must be able to detect the environment and understand it. They must be able to cooperate in planning and making decisions. They should preferably be able to operate and function under strong interference, as they operate in a complex environment and the data link may be unstable. They need to do real-time obstacle avoidance, both to avoid hitting each other and hitting obstacles. In addition, the swarm is controlled in some manner by a human, and the interaction between the swarm and one or more human operators is important.

Drones already play an important role on the battlefield today. They are very important for surveillance and situation awareness, and both large and small drones also carry weapons and

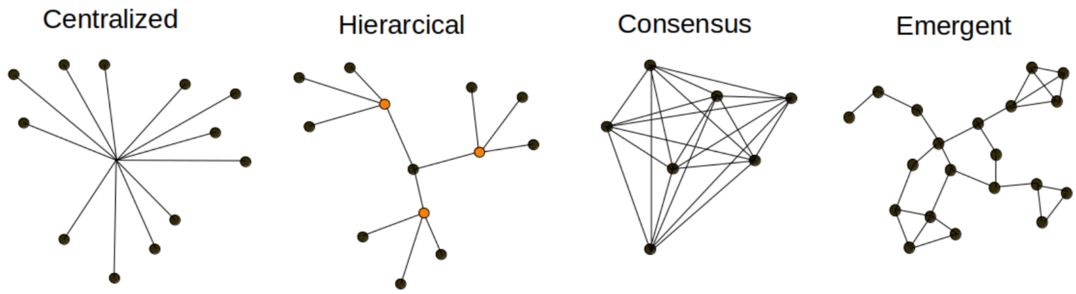

Figure 2.1 Examples of swarm architectures. Adapted from [7]

destroy targets. While several drones often are used simultaneously, they have so far mostly been operated independently, and are thus not true drone swarms [10].

2.1 The swarm and drones used for simulations

The drones used in our simulations are small Class I quad-copter drones, typically weighing less than 10 kg and having a range of less than 10 km. The drones were a mix of surveillance drones and loitering munitions ("suicide drones"). We call the surveillance drones Flamingo (see [2]), and the loitering munitions Svale (see [1]). The simulated Flamingo drones are made as similar to their real world counterpart as possible. The real world counterpart of Svale has not been flown with a warhead, but are otherwise similar to the simulated Svale. In the simulator, drones take off and land on unmanned carrier vehicles. One carrier vehicle can carry and serve ten Svale plus ten Flamingo drones. The Flamingo drones had good IR and daylight cameras in a gimbal, while the Svale drones had cameras with a narrow field of view pointing directly forward. The Svale and Flamingo drones are shown in figure 2.2.

Figure 2.2 Svale (left) and Flamingo (right).

The available drones can be organized in one or more swarms, and an operator can assign drones from one swarm to leave it and join another swarm. A swarm can be given several different orders. The drones in that swarm then each decide how they should contribute to that task, and each drone knows the position and status of the other drones in the group. This means that the architecture is close to the "emergent" architecture described in [7].

The drones are controlled by an operator using Valkyrie Ground Control Station (GCS). This user interface is used to control real drones as well as simulated drones. Valkyrie GCS has a map showing the position of all drones and their observations, and several tools for supervising the drones and giving orders to them. More details about Valkyrie GCS is found in section 3.1.

3 Setup

The setup we used represented an operator position of a drone swarm operator (see figure 3.1). It consisted of Valkyrie GCS (see section 3.1) as the main system for the swarm operator, and a BMS as the C2IS (see section 3.4). There are also two simulation components, firstly MASIM (see section 3.2), which is the internal simulation component of Valkyrie GCS, and VBS4 (see section 3.3). MASIM simulates the drone entities, and VBS4 simulates the scenario, which includes the scenario entities. VBS4 also serves as an image generator for the Valkyrie GCS.

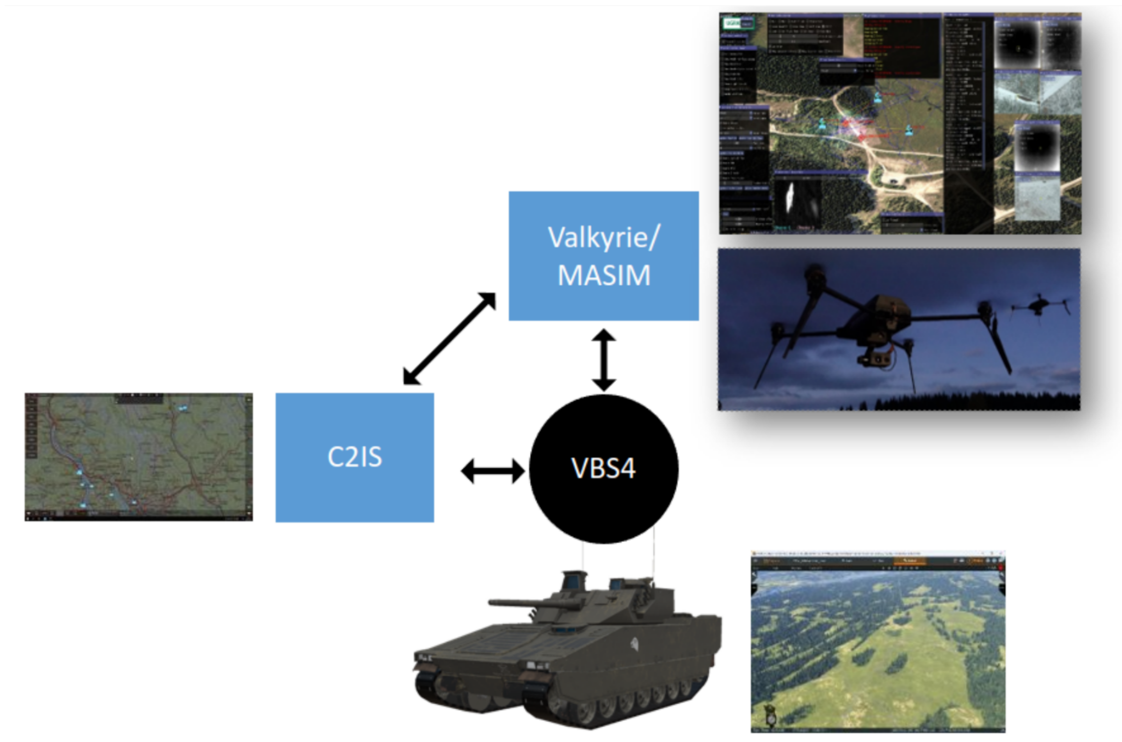

Figure 3.1 Simulation setup

In our simulator setup (see figure 3.1, there is a synthetic terrain in both VBS4 and in MASIM. These are generated from the same source in order to get them as similar as possible. However, there will still be some differences. For instance, vegetation and buildings in MASIM come from a surface height model, while in VBS4, vegetation and buildings are generated and placed on top of a ground surface. This means that the heights of trees and buildings will not be an exact match.

MASIM handles the simulation of the drones, while VBS4 simulates all the other units. The drone operator can see the video stream from one selected drone. In our simulation, this video stream is a VBS4 client showing the camera view of the selected drone. Figure 3.2 shows a screenshot from VBS4.

Figure 3.2 Screenshot from VBS4

3.1 Valkyrie Ground Control Station

In our simulations, the drones are simulated in MASIM. This simulator handles how the drones move, based on their orders. They are controlled from the user interface Valkyrie GCS. The operator can select any number of active drones, and give them an order. These will then cooperate in carrying out that order as best they can. The interface displays the position of every drone on a map. It is also possible to see what area the camera of one specific drone covers. Areas that have recently been examined by drones are marked in a slightly different hue, to give the operator an indicator of what areas have been covered. There are several available orders. A swarm can for example be told to cover a certain area, or a certain path out to an area. They can be set to screen a sector, looking for targets that move towards own units. They can also be told to follow targets they detect, or to attack detected targets. These are just examples of many possible orders that can be given to the swarm.

With a screen order, the drones are given a section of a perimeter to screen. The drones divide the section between them, and if the section is too large for the drones to cover the entire section simultaneously, they will each patrol a part of the section, making sure the entire section is covered. When they start running low on battery, new drones are sent from a base (which in the simulator is an unmanned carrier vehicle) to take over for those who need to return to recharge. In a search area order, the drones divide the area between themselves, and try to cover the entire area as fast as possible. Given a search axis order, the swarm follow a certain route and try to cover the area along that route as best as possible, from several different angles. These are just examples, there are several other orders as well, including orders where single drones depart the swarm to follow detected targets, and orders to make Svale drones attack detected targets.

If a drone detects something, the operator gets a warning, and an easy way to get an image from the relevant drone's camera. The possible target also appears on the map. The operator can then decide to confirm or reject the observation. The drones try to figure out if they see the same target, to avoid multiple reports of one single target. A screenshot of Valkyrie GCS is shown in figure 3.3

Figure 3.3   Valkyrie Ground Control Station (GCS), the interface for operating the swarm.

3.2 MASIM

MASIM is a simulator for drone swarms, used with a user interface for controlling the drones (Valkyrie GCS). The user interface is the same as is used for operating drones in the real world. Masim has a synthetic environment in which the drones fly. Since we are connecting two simulators, Masim and VBS4, it is important that the terrain and vegetation in the simulators are nearly identical. Masim and VBS4 are the main components of our setup.

3.3 Virtual Battlespace (VBS4)

Virtual Battlespace 4 (VBS4) is an interactive, three-dimensional synthetic environment, for use in military training. VBS4 is developed by Bohemia Interactive Simulations, and is based on game technology from the commercial game series Armed Assault (ARMA). VBS4 is used for training purposes by many military organizations, including the Norwegian Army, and it has it has become and industry standard in game-based military simulation [11]. VBS4 is designed so that one player controls one soldier. It is also possible to use an AI to control units, giving them various orders.

3.4 C2IS

We have also connected the simulator to norBMS and the Norwegian Command Control and Information System (NORCCIS). norBMS is the Battlefield Management System (BMS) used by the Norwegian Army. These systems have not been important for our experimentation so far, but it is important that we are able to connect our simulator to the actual Command, Control and Information System (C2IS) used by the Norwegian Army. We also have an in house BMS available.

4 Experiments

The focus of our experiments have been on how to operate a swarm of small drones, both how the interface should work, and how the swarm should be used to best support a maneuver unit. We have been developing both the simulation setup and Valkyrie GCS during our experiments, so the experiments have helped both improving the interface and improving the simulators and setup. During our experiments, we have usually had one person control the drone swarm, one person control the unmanned vehicles, one person play the commander, and one person handle the RED forces. Blue side then carried out their mission, which varied from scenario to scenario. Our focus were on how to use the drone swarm, meaning both how to operate it (how should the interface work, how many drones can an operator handle, what aid is required to operate them successfully) and how to get the most out of them operationally.

The drones are launched from a base, and also need to return to a base to recharge their battery after some time. In our experiments, the bases were unmanned "carrier vehicles"; unmanned vehicles for transporting and charging drones. The battery time for small drones can be a limiting factor for their operations. In some of our experiments, we saw that it was beneficial to have the base which the drones launched from and returned to, close to the front, as they had to fly some time before reaching the area where they were supposed to operate. They would later have to fly the same distance back before their battery ran out, leaving a limited time over the target area. If the base was further behind, some of the areas we now reached with the drones, would have been too far out for them to reach. With only one carrier, the entire swarm would be in jeopardy if the carrier was taken out. Therefore it seems important to have redundancy in the form of more than one base for the drones.

In our simulations, the drones has always had image recognition except when we tested how things would work without it. How the image recognition has worked has changed slightly during our experimentation. In the early stages, all drones would detect any target that was within their sensors' covered arc and within a certain distance. At that point, trees and vegetation was not taken into account, so even targets in woods were always detected. At a later stage, trees and vegetation were taken into account. We were able to add "false targets", simulating hot spots in the terrain, which was also reported as targets by the drones. Also, there are several types of targets: Is it a civilian or military target? Is it a person or a vehicle? The real drones are supposed to be able to classify targets to some degree (distinguish between personnel and vehicles, for instance). In most simulations we allowed MASIM to make this distinction, but in some simulations all observations were just reported as general observations. False targets were reported as personnel when we allowed classification.

4.1 Scenarios

We have been experimenting with different scenarios at a low tactical level. Typically, we operate a swarm of UAVs, a command vehicle, and a small number of UGVs on blue side. Red side generally does not have UAVs, only infantry and Infantry Fighting Vehicles (IFVs). Some, but not all of the scenarios, include false targets which the drones may detect. The scenarios we have used are presented in this chapter.

4.1.1 Scenario Convoy

This scenario was designed for just testing various functionality without enemy interference. In particular, we tested how attack drones should home in on moving targets, but other aspects were tested as well.

Red side consists of a convoy of vehicles which moves along a road at constant speed. They will not change behaviour even if they are attacked, and they will never open fire.

Blue side has a command vehicle and a swarm of drones, both surveillance drones and attack drones.

Neither Blue nor Red had any specific mission statement in this scenario, as it was more of a sandbox for testing functionality

4.1.2 Scenario Attack

In this scenario, Red is holding an area, and Blue intends to capture this area. There are still civilians in the area, particularly in the north west area, where blue is starting the scenario. The scenario is illustrated in 4.1.

Blue consists of a main force, which is not an active part of the scenario and whose size is not important. Blue also has a reconnaissance platoon, consisting of a command vehicle (CV9031), two armed UGVs, two carrier UGV, and a swarm of UAVs (both surveillance and attack drones). This platoon is the important part of the scenario.

Red force has a company size unit in the target area. In addition, reinforcements of several mechanized companies arrive along a western road.

The goal for the Blue recon platoon is to secure the flanks of the axis along which the Blue force advance. They are also to identify the front line of Red defensive units in the target area, without engaging in decisive battle. It is also of value for Blue to know how far the Red reinforcements in west have advanced. He must also consider the possibility that small units from these reinforcements may try to cross the difficult terrain between east and west, to disrupt the advancement for Blue.

When playing this scenario, we had one player control the drone swarm, one player control the UGVs, and one player acting as "battle captain". In addition, one person controlled the red units and also moved the blue main force according to the progress and reports from the blue battle captain.

4.1.3 Scenario Defense

Blue side consists of a recon platoon, consisting of a command vehicle, two armed UGVs, two carrier vehicles and a drone swarm.

Red side consists of several independent units. It is not one side, rather there are several different factions. This is meant to simulate a setting with several independent actors, who may or may not be hostile to us. There are three separate BMP-3 platoons and two separate infantry squads, for a total of five possibly hostile factions.

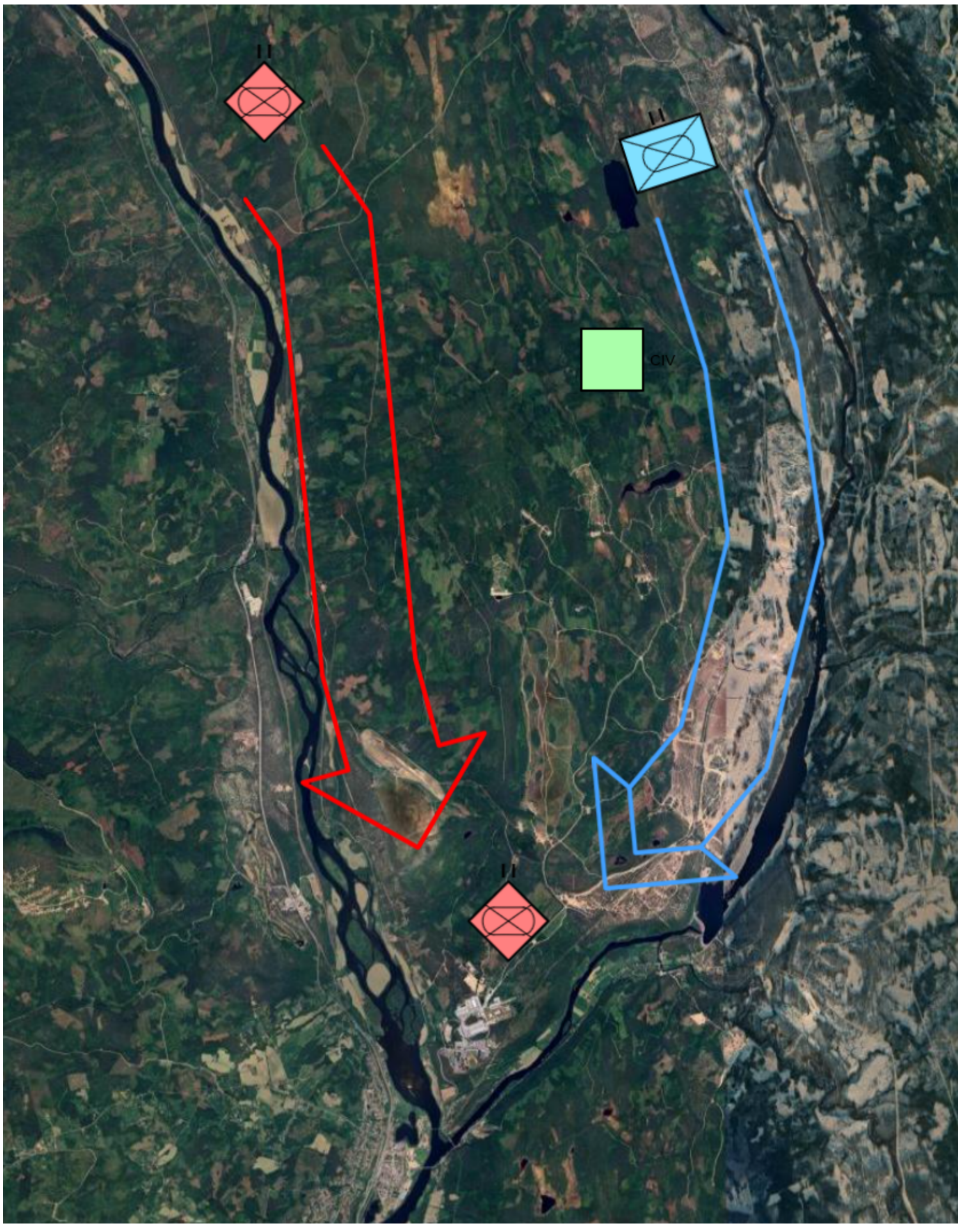

Figure 4.1 Scenario Attack. Red symbols denote enemy units, Blue symbols denote own units, and green symbols denote civilians.

Blue task is to defend his base against threats from any of the Red factions, while not provoking or attacking any of the factions that are not posing a threat. Blue knows about suspected enemy activity in the area. It is also known that there are civilians in the area. In this scenario there were no "false targets" (e.g. hot areas in the terrain which the drones would detect as targets), however, this was not known to the operators.

There are two separate infantry squads and three separate BMP3-platoons on RED side in the scenario. Only one of the IFV-platoons and one of the infantry squads are actually trying to attack the Blue base. The position of RED and BLUE is shown on the map in figure 4.2. It is worth noting that the infantry squad in the north west part of the map is in an area with relatively dense woods. The RED units moving towards the airfield, move close to or through areas with civilians. No RED units are considered to be a likely threat against the civilians, but BLUE may (obviously) not engage civilian targets either.

4.1.4 Symmetric opponent scenario.

In this scenario, both Red and Blue have the same assets. They each have one command vehicle, two unmanned carrier-vehicles, and two unmanned armed vehicles, plus a drone swarm. All drones were surveillance drones in this scenario; neither Red nor Blue had attack drones.

The aim for both Red and Blue was to locate the command vehicle of the opposing team (with the understanding that if it is located, it can be destroyed by indirect fire).

4.2 Lessons learned from our experiments

In many cases, the commander had several tasks for the swarms simultaneously. Often the swarm had to cover a lot of area and do several things at once. With a swarm of around 40 drones this was difficult, but usually doable. The drones ability to automatically detect targets were important in making this possible. In our scenarios, "targets" in this case includes civilians and hot spots in the terrain as well as real enemies, but what matters is that the operator could focus on video/images only from areas where the drones reported seeing something, rather than having to try to manually watch every video stream simultaneously to look for targets.

The presence of civilians, as well as other false targets in the area, made searching slower for the operator, and took a lot of his focus. It takes time to dismiss an observation as not being a threat. Declaring an area as safe, or at least void of enemies, can be time consuming.

When using the command vehicle and swarm as reconnaissance, this recon units did not advance any faster than what we would expect of an traditional recon unit without access to a drone swarm. Rather, the resources were spent looking at more areas, and making "more sure" that it was safe, before having the main force advance. It would be interesting to actually play both types of recon units in several scenarios to see if this would usually be the case, or if it would also some times be used for faster rather than "better" recon. Even if the unit did not move faster than we would expect of a traditional recon unit, it did cover a larger area faster.

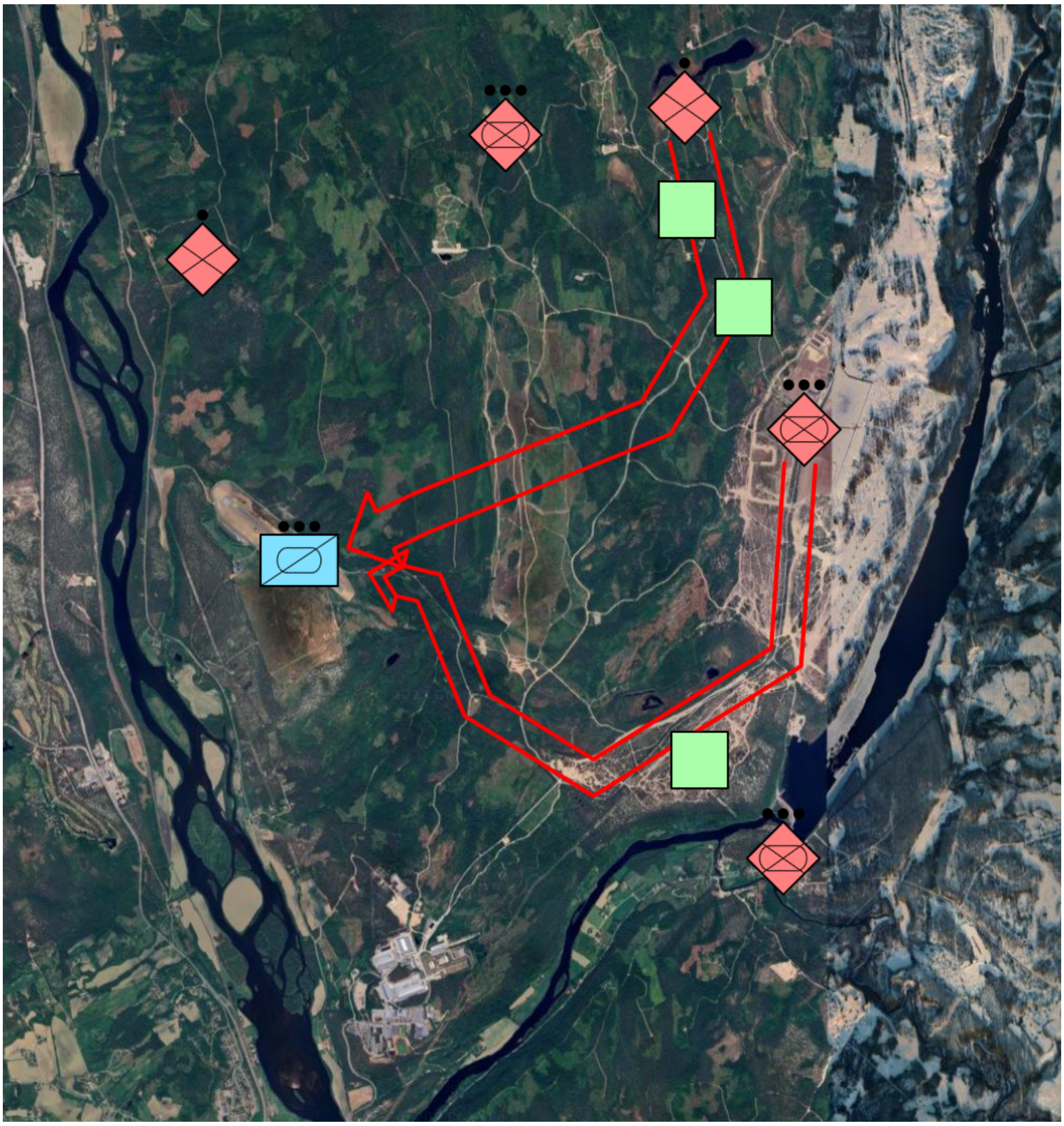

Figure 4.2 Scenario Defense. Red symbols denote enemy units, Blue symbols denote own units, and green symbols denote civilians.

In the symmetric opponent scenario, both Red and Blue deployed their drones and started searching. As we have seen in other scenarios, the small UGVs were too slow to keep up with the pace of the drone swarm. After some time, we ended with a situation where both Red and Blue felt happy with their situation. Both sides had located the enemy's command vehicle, yet neither side was aware that their own command vehicle was compromised. The drones' ability to detect other drones are very poor (they mainly look downward, and due to the small signature of the drones, they can only detect them at a very close range). In this scenario, the Red and Blue swarms had nearly flown through each other without noticing each other. Without a radar, the command vehicles were not able to detect the enemy drones either.

Playing the symmetric opponent scenario reminded us of the importance of being able to detect enemy drones. This is probably easiest done by a radar. Preferably a Counter UAV System (CUAS) should be part of the force structure, to not only be able to detect drones, but also defeat them. When having a drone swarm that covers a large area, it would have been very useful to also be able to detect enemy drones from drones in our swarm. They often make up the screen of the maneuver units, and should detect incoming threats. However, at least with the very small kind of drones we have been looking at, having sensors which are able to detect enemy drones at a significant distance may not be feasible. They may be able to detect small enemy drones at short distances, though. If the swarm is sufficiently large, and deployed at several heights, then perhaps it will also be able to detect incoming drones with an acceptable probability.

We have seen that confirming that false targets actually are false targets can require a lot of the operators focus for some time. False identifications needs to be followed up to check if they are real targets or not, and while it can sometimes be easy to dismiss an observation as false, other times it may require a lot of time, and looking at the area from multiple angles. We have seen the operator being so focused on trying to determine which targets were real or not in one area, that he missed a lot of important things happening in other areas the swarm was covering.

For scenarios to give realistic results, it is important that it takes some time from scenario start until RED forces get to areas where they can be detected by BLUE drones. In the early stage of a scenario, it is easier for the drone operator to put up screens and make sure the drones covers the areas they are supposed to. Later, when drones have to return to base to recharge, and are replaced with new drones, a more chaotic situation arises. It is during such periods that it is easiest for RED to approach his target undetected. This highlights the need for good procedures for recharging and cycling drones in an orderly manner.

5 Using a swarm to support maneuver units

5.1 Advantages and disadvantages of a swarm of small drones

5.1.1 Size of the swarm

How large is a swarm? There is no clear definition of this. Both the size and types of drones should be suitable for the operation it is used in. In our experiments, a swarm has usually consisted of 20-40 drones, of which some have been surveillance drones while others were loitering drones. However, not all drones have been in the air at the same time. They need to return to a base and recharge their batteries, and then other drones will fly out and take their place.

With a large number of drones, it becomes inherently difficult for an operator to observer the streamed data from every drone all the time. Some form of automatic target recognition or AI is needed to assist the operator, so that an operator can use the swarm effectively.Our observations suggest that without any image- or automatic target recognition system associated with the swarm system, an operator would be limited to around five drones (a "flock" instead of a "swarm").

There is also a case of logistics when it comes to drone swarm sizes. In our experiments we used an autonomous ground vehicle as a drone carrier, but in theory this could be any carrier vehicle as long as the vehicle can automatically retrieve and launch drones. This would of course mean that a maneuver unit would need extra vehicles for this purpose. Another alternative that became apparent in the experiments was that one could rig each vehicle in a unit with a drone cartridge of 2-4 drones, with an automatic launch and retrieval system, and if the drone swarm system supports some form of "bring your own drone", one could distribute a drone swam on existing vehicles within a unit. This means that a company sized vehicle unit of 10 vehicles could bring 20-40 drones.

5.1.2 Battery capacity and range of drones

The exact battery capacity of a small drone will vary from one type of drone to another, and it also depends on the weather conditions and how it is operated. Between half an hour and one hour may be common for drones of the size we have simulated, although this may increase with further technological advances. This allows such drones to fly somewhere between 3 and 10 kilometers before they need to return. If they are to do something besides just fly out to a position and back home, this distance will naturally be reduced. Larger drones will obviously have different characteristics. The drones used in our simulations have a range of around 8 km before they need to return to recharge. Since they usually need to spend some time in the target area, the effective range is shorter.

It is our opinion that a drone swarm system within a manoeuvre unit at least should cover the range of its nearest organic indirect fire assets. In most cases, this would mean within the effective range of a unit' mortar systems, with effective ranges commonly within 5-10km.

5.1.3 Sensor package

For surveillance, drones need to have both daylight cameras and IR cameras. Decent IR cameras are expensive, but they greatly improve the likelihood for the drone to detect targets, even in daylight. At night, they are a must, as ordinary cameras will not see anything. If small drones are to have the ability to attack ground targets, they will most likely have to be suicide drones, as drones of this size are unable to carry and fire missiles. They have to be the missiles themselves. It is desirable that suicide drones have a relatively low cost, as they are single use. Using other drones for locating targets, one can use less expensive cameras in the attack drones, with a smaller field of view, intended for locating and following the target at relatively short distances. Large drones may also carry radars and other sensors, but small drones do not have the payload capacity for such sensors.

5.1.4 Target identification

With cameras as their only sensors (IR and daylight), the drones need line of sight to a target in order to detect it. This means that personnel in dense vegetation or in buildings will not be detected. Even vehicles under dense vegetation may be hard to detect. Often it is just as important to know which areas have been examined without any targets detected, as where targets have been detected. It is important to remember that in areas the swarm has covered, there may still be targets in buildings or vegetation in the area.

5.1.5 Situational Awareness with drones

There is no doubt that access to a swarm of drones greatly increases the situational awareness for a platoon commander. He or she will rather quickly be able to determine if an area is safe or not, and locate targets in the area. Access to indirect fire or attack drones may make it possible to attack such targets without exposing oneself directly to the enemy. Using Augmented Reality (AR) to display the targets positions in the sight of the gunners will give an advantage if the platoon has to engage the enemy directly.

5.1.6 Indirect fire

The use of surveillance drones will increase situational awareness on a lower echelon level, and in turn, will increase potential target inflow. This is obvious in a synthetic setup, and it is also the experience from live experimentation. If the autonomous swarm aspect with automatic target detection is added, the likelihood of target inflow will increase further. This of course means opportunities in regards to indirect fire and target engagement. It is our opinion that there needs to be sufficient indirect fire assets available on a lower echelon level to handle the target inflow, when employing drone swarms in manoeuvre formations. The indirect fire assets should be varied, and range from loitering munition in form of drones and automatic grenade launchers on remote weapon stations to more traditional systems like artillery and long range precision fires. One key aspect here is time from target identification to effect on the ground, which need to be sufficiently short. This in turn means that a drone swarm system should be an integrated part of the combat formations, and be able to share target information and data directly to the fires chain.

6 Conclusion

It is difficult to predict how we will end up using drone swarms - or any emerging technology - in the future. However, based on our experiences, we will make some conjectures. Both when making scenarios, designing interface, running simulations and during discussions, we keep making observations and predictions which we believe will prove useful. In this chapter we present our thoughts about the future use of drone swarms.

6.1 Consequenses for maneuver units

A swarm of small drones used by a maneuver unit can enhance the unit in several ways. Mainly, though, it provides situational awareness for the unit. A swarm of drones can cover a rather large area in a relatively short amount of time. With the ability to rotate new drones in when those currently in the air are returning to charge their batteries, they can also cover the area continuously. With good sensors and a good AI for automatic target detection, this means that the maneuver unit will be able to see any target within a range of around 5-7 km (probably more in the future), unless they are inside buildings, covered by dense vegetation, or very well camouflaged.

With suicide drones as part of the swarm, the drones will not only be able to detect targets, but may also attack them. The effectiveness of suicide drones will depend on the swarms ability to precisely locate and track targets, the warhead of the suicide drone, and the armour and defence measures of the target. Small drones may fly at a low altitude, and they are hard to detect on long ranges. In order to be able to detect, track and destroy small suicide drones, a maneuver unit will likely need an organic anti-drone system, rather than depend on air defence from higher level echelons. Since the enemy will also be using drones, employing such anti-drone systems will be important. The drone swarm can itself be part of an anti-drone system. They can for instance get a track of enemy drones from a ground based radar, and then suicide drones can intercept incoming enemy drones.

6.2 Organization

There will most likely emerge swarms of drones of many different categories of drones. Swarms of large drones will probably both be organized and operated quite differently than swarms of small drones. In this report, we only consider small drones, as described in chapter 2.1

In the short term, swarms will not be fully autonomous. While a fully autonomous swarm would be able to receive an order, and then operate independently of human input, both autonomous and less autonomous swarms will need one or more operators with a control system. We believe that such an operator - or operators - will not need to be in the very front, even if the swarm flies ahead of own units and support the vanguard. The drones may need a base from which they take off, and where they can return to recharge batteries, to be close to the front, but the operators do not necessarily need to be in that same position. The main reason for an operator to be close to the front units, is the link between the swarm and the operator. A longer distance means more issues with maintaining a good connection, and with retaining a high bandwidth. This can in part be remedied by designating one or a few drones in the swarms as relay drones. We believe that while the base or bases for the swarm may need to be at the front to support a platoon in the front, the swarm operator or operators should be a bit further back. Losing the operators may mean losing the entire swarm, and so they should be protected by not putting them in the very front. How far behind they could/should stay may depend on several factors, but given sufficient bandwidth, there is very little to gain and a lot to lose by placing them in the front line.

A swarm could consist of a lot of drones; far too many for one operator to be able to watch the video streams from each drone. For a swarm to be efficient, it must therefore have some level of image processing and recognition ability. Operators will give the swarm its missions, and confirm, reject or edit observations made by drones in the swarm, who will alert the observer when they think they find something, and give him an option to see an image or a video of what was detected. For anyone but the operator, getting video and images from the drones is likely going to take focus from other tasks while not adding much value. For a platoon commander, it is better to get the processed data, in form of what areas have been scanned, what has been detected, and tracks of targets currently being monitored. For a gunner, getting the positions of relevant targets into their sights as AR symbols is probably the best way to receive data.

Depending on the size of drones, the command of the swarm will likely be placed on different level echelons. However, drones like the ones we have examined have limited range, and will therefore have to be launched from relatively close to the front in order to aid the front units. This also means there is a limited area they can cover. This indicates that a swarm of this type of drones probably belongs at the company or even platoon level, definitely not higher than battalion level. Swarms of larger drones will naturally belong on a higher level.

6.3 What will change with swarms

The way battles are fought changes over time, but also depending on who the sides of the war are, and what what sort of war is being fought. Combat evolves, and the emergence of drone swarms is part of this evolution. However, it is our belief that even if drones and drone swarms will greatly increase situational awareness, both for us and the enemy, most aspects of combat will remain similar to how they are today. Despite drone swarms entering combat, mechanized units will be needed to take and hold ground. There will be an increased need for air defence and drone defence. We will most likely also see drone swarms fighting enemy drone swarms. We must expect enemy drones to see almost everything we do, and likewise, our drones will be able to see most things the enemy does. We believe this will call for increased use of decoys and deception. It also means that since more targets are detected, there will be more need for long range fire to hit those targets.

Acronyms

AR Augmented Reality

BMS Battlefield Management System

C2IS Command, Control and Information System
CUAS Counter UAV System

GCS Ground Control Station

IFVs Infantry Fighting Vehicles

MASIM Multi-Agent Simulator

NORCCIS Norwegian Command Control and Information System

SA Situational Awareness

UAV Unmanned Aerial Vehicle
UGV Unmanned Ground Vehicle

VBS4 Virtual Battlespace 4

References

[1] Eilert André Mentzoni et al. *"LandX22 - Experimentation with uncrewed systems in a future combat unit"*. FFI-rapport 24/00357. Norwegian Defence Research Establishment, 2024.

[2] Olav Rune Nummedal. *"Flamingo - a UAV for autonomy research"*. FFI-rapport 21/00318. Norwegian Defence Research Establishment, 2021.

[3] USMC MAJ Kate L. Murray. *"Early Synthetic Prototyping: Exploring Designs and Concepts Within Games"*. NPS-AM-14-191. Naval Postgraduate Shcool, 2014.

[4] Marius Halsør. *"Simuleringsøvelse med VBS2 - test av BMS og Augmented Reality"*. FFI-rapport 2012/00613. Norwegian Defence Research Establishment, 2012.

[5] Martti Lehto and Bill Hutchinson. 'Mini-drones swarms and their potential in conflict situations'. In: *15th international conference on cyber warfare and security*. Vol. 12. 2020, pp. 326–334.

[6] Dominika Kunertova. 'The war in Ukraine shows the game-changing effect of drones depends on the game'. In: *Bulletin of the Atomic Scientists* 79.2 (2023), pp. 95–102.

[7] Paul Scharre. 'Robotics on the battlefield part II'. In: *Center for New American Security* (2014).

[8] Tadeusz Zieliński. 'Factors determining a drone swarm employment in military operations'. In: *Safety & Defense* 1 (2021), pp. 59–71.

[9] Zhu Xiaoning. 'Analysis of military application of UAV swarm technology'. In: *2020 3rd International Conference on Unmanned Systems (ICUS)*. 2020, pp. 1200–1204. DOI: 10.1109/ICUS50048.2020.9274974.

[10] Zachary Kallenborn. 'Swarm talk: Understanding drone typology'. In: *Modern War Institute* 10 (2021).

[11] Per-Idar Evensen. *"Modelling and implementaion of a generic active protection system for entities in Virtual Battlespace (VBS)"*. FFI-report 17/00879. Norwegian Defence Research Establishment, 2017.

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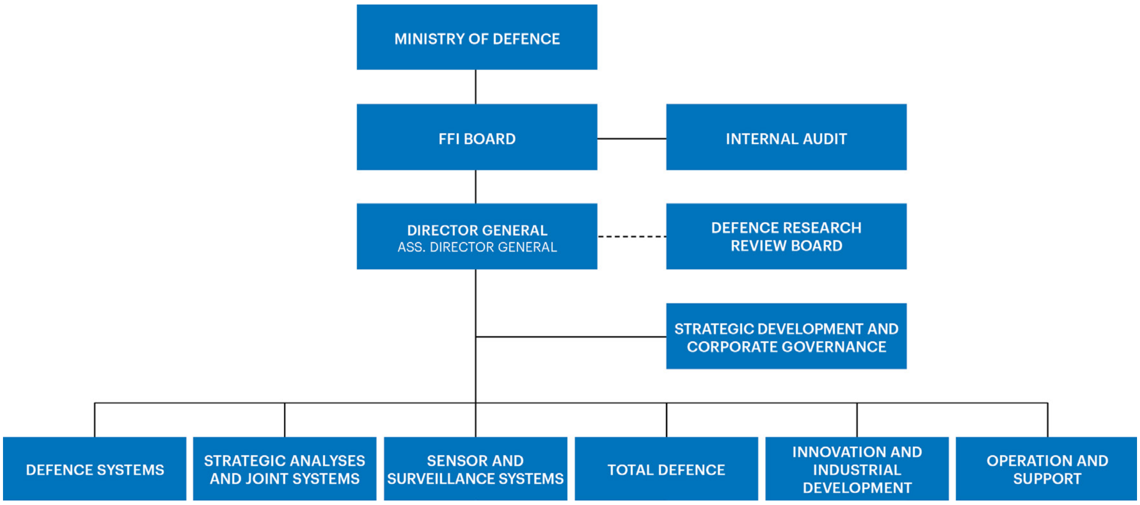

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