Toward Defining Canadian Manned-Unmanned Teaming (MUM-T) Concepts

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Abstract

As unmanned aerial vehicles (UAVs) mature from a capability developed during conflict into a standard element of nations' inventories, it is becoming more critical to consider how useful a UAV fleet might be across a wide spectrum of missions prior to their acquisition. As the reliability of automation increases, unmanned systems are given greater freedom of movement and action in light of the growing trust from the users. As a consequence, unmanned aircraft need no longer act in clearly different roles and airspace, and may instead closely support manned aircraft to achieve greater mission success in a wide range of traditional and non-traditional roles. The authors developed and executed a hierarchical decomposition method to evaluate the utility of a broad range of UAVs to a broad range of missions, specifically those that could be executed in concert with Canada's fighter and maritime patrol aircraft. Based on these results, initial advice is developed for both research and requirements staff on what types of UAVs will be most widely applicable to Canada's needs. Rather than providing an absolute ranking, the method is designed primarily to greatly narrow the decision space, so that the remaining options can be evaluated in more detail by technical and military experts. The conclusion will examine the impact of the expected level of inter-aircraft interoperability (using e.g., NATO STANAG 4586) on the highly rated options, as well as the associated autonomy requirement.

Introduction

The use of UAVs in a military context is now fairly commonplace. Moreover, it is not unusual for manned and unmanned aircraft to collaborate while working toward a common military goal. In such a scenario, each aircraft may use its strengths to offset the other's weaknesses, with such pairings intended to increase mission success. This may lead to specific unmanned capabilities being rapidly developed and fielded to fill specific gaps in manned aircraft capability. This is particularly common during wartime, when demands are at least partially driven by the needs of specific theatres matched with high technology readiness level (TRL) solutions, without an overall assessment of the long-term needs. Although notionally working together, the aircraft are generally disconnected from one another (often with the enforcement of strict altitude separation) or used as standalone capabilities without regard for the potential efficiencies introduced by the concept of manned-unmanned teaming (MUM-T).[1]

When studying the concepts of integration and teaming, there is a tendency to automatically consider current commercial/military off the shelf (C/MOTS) solutions for both manned and unmanned aircraft. Although high TRL and a rapid deployment of capabilities are achieved, one can easily lock in to existing and temporary problems and solutions, or field sub-optimal systems that have been designed to solve different problems. On the other end of the spectrum, if C/MOTS solutions are not explored, research proposals may suggest new technology with a narrow focus to solve outstanding difficult niche issues – e.g., unmanned aerostats for remote Arctic surveillance – which may result in prototypes

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[1] MUM-T is defined here as the use of manned and unmanned [aerial] vehicles in concert, i.e., when they can influence each other's course of action (Arbour, Bourdon, and MacLeod 2012).

either falling short of (or not being generally applicable to) other requirements, or suggesting new technology to solve a wide class of problems with complex and expensive systems. Finally, given the costs associated with procuring new manned aircraft, focus is more often than not put on procuring new unmanned capabilities based on the unproven assumption[2] that it will be faster and cheaper to acquire and operate UAVs. Pairing today's manned aircraft with available (or currently high TRL) UAVs may cause militaries to ignore mid- to long-term warfighting needs, while experimentation may fail to identify the right lessons for the aircraft of tomorrow by using restrictive assumptions or limiting experimental parameters.[3] Lastly, experimenting with C/MOTS systems may also fail to recognise the synergies and efficiencies that could be achieved by developing MUM-T as a system with purpose-built sub-systems, rather than simply choosing combinations of pre-existing parts.

Complicating matters further is the fact that most militaries – particularly in nations such as Canada that have small to medium-sized armed forces – cannot afford to maintain many different types of equipment. It is thus important for decision makers in both research and acquisition to be presented with a comprehensive assessment of what types of platforms may be useful across a wide array of missions before rushing to acquire or develop specific solutions. Otherwise, developing a MUM-T team part by part for the problem(s) found in a specific theatre increases the risks of ending up with several niche assets, with little to bring to the next conflict.

In the current fiscal context many countries are facing, efficiencies must be found in order to 'do more with less'. This problem may sometimes be resolved through the use of capability-based planning in order to evaluate the capability – or effect – one is trying to achieve in a military action in order to plan future fleets. However, the capabilities achieved by MUM-T may often be misunderstood. In particular, the combined effects generated by teaming aircraft may not be properly accounted for; rather, they may be seen as distinct contributors to mission goals whose value is limited by the capabilities they individually provide. Solutions engineered to seamlessly work in a cooperative fashion may therefore be overlooked in favour of capabilities one assumes can be integrated in the future, introducing potential financial and mission risk.

While teamwork is a natural means of overcoming problems in many settings of everyday life, the concept of MUM-T, with multiple aircraft acting as one (rather than multiple aircraft operating as a set of parts) has not been widely embraced. As a team, in the true sense of the term (i.e., where each individual works together to achieve a common goal), each can influence the other with its actions in order to modify a pre-defined and agreed-upon course of action. In a MUM-T concept, this can be achieved by much more than through the manned aircraft obtaining direct control of the UAV's flight and airframe. NATO STANAG 4586[4] defines five levels of interoperability (LOIs) starting at UAV control through a third party (LOI 1) up to full control of the UAV within the manned cockpit (LOIs 4 and 5). Performing the same mission at a different LOI would result in the mission unfolding differently, and with varying degrees of success. Using the right LOI for the mission at hand is a challenge in itself.

It is clear that each LOI may necessitate a different UAV, or UAV type, which may not be a C/MOTS UAV built as a stand-alone system. But it is often forgotten that each LOI

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[2] The notion that UAVs are cheaper than manned aircraft is often used to justify their purchase, or at the very least to justify their use in dangerous situations as disposable assets. However, as noted in DOD (2013, 3): 'The size, sophistication, and cost of the unmanned systems portfolio have grown to rival traditional manned systems.'

[3] 'Today's problems and their solutions may not solve the problems arising 20 years from now' (DOD 2013, 9).

[4] NATO 2012.

may also necessitate a different definition, or level, of autonomy on the UAV's part. By purchasing UAVs with built-in autonomy (from C/MOTS), defence departments implicitly agree with industry assumptions regarding the UAV's usage, rather than having industry design the right UAV for their needs. The autonomy level used for MUM-T experimentations may thus be improper for the expected LOI to be achieved, or workarounds must be put in place to offset the autonomy's limitations, thus further reducing the realism of the trials.

In the case study summarised herein,[5] the authors were asked to examine the use of manned and unmanned aerial vehicles in concert, i.e., when they can influence each other's course of action, including whether there was any advantage to integrating them for use together, rather than treating them as separate fleets.[6] Although a meaningful decomposition of the MUM issue and a suitable assessment methodology were put in place, the MUM-T problem in the Canadian context is far from being resolved. General conclusions for the best UAV type, and the best UAV role, in support of two types of manned aircraft have been reached, but the interaction and autonomy levels necessary to achieve the perfect teaming, all the while ensuring fiscal viability and UAV multi-role capabilities, have yet to be pursued.

The intent of this chapter is to share Canada's experience in assessing the utility of UAVs in MUM-T operations, and to discuss how a similar approach may be used to explore the utility of acquiring or developing autonomous vehicles more generally. First, a description of how to decompose the problem space will be provided. This is followed by a brief overview of the mathematical underpinnings of the work.[7] Next, some conclusions from the original study will be discussed, leading to an assessment of possible follow-on work. Finally, conclusions relevant to the policy maker are drawn in the hope that this will encourage a more broad-ranging thought process when considering requirements for autonomous system research, development, and acquisition.

Structuring the Problem

The Canadian case study under the Manned-Unmanned Aerial Vehicle Interaction (MUAVI) project examined how useful the MUM-T concept would be for enhancing the ability of both the Canadian maritime patrol aircraft (MPA) and the Canadian fighter aircraft to achieve mission success. This included the current platforms (CP140 Aurora and CF188 Hornet, respectively) and their potential replacements. This chapter focuses on the underlying question of how UAVs can make a fighter aircraft more effective or efficient at its tasks when the MUM-T concept is employed, although will discuss the results of both analyses. In particular, this chapter explores possible MUM-T combinations and identifies the most useful avenues, while addressing lingering questions regarding the meaning of MUM interactions and UAV autonomy.

Many factors must be considered in this question. Both the MPA and the fighter are expected to accomplish a breadth of missions, especially in smaller militaries with limited fleets, in which an aircraft may need to perform duties that extend beyond its original purpose and capabilities. There is also a wide variety of UAVs – encompassing every class of manned aircraft as well as some that could never house a human occupant – each with their own strengths, weaknesses and predefined expectations vis-à-vis their employment. This makes for a large number of possible MUM pairings.

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[5] Although initially restricted to distribution within defence departments, the initial report on the case study has since been fully released under Access to Information request A-2014-00254 (National Defence and the Canadian Armed Forces 2014). See also Arbour, Bourdon, and MacLeod 2012.

[6] Elements of this approach were also used in a workshop on the potential threat posed by the use of unmanned air/surface/sub-surface vehicles in the maritime environment (Haché 2013).

[7] For a more generalised treatment of the method, see Bourdon, Arbour, and MacLeod (2014).

Structuring the problem space has been accomplished by developing a process to decompose the manned *platforms* – MPA and fighter – and UAV *types* (described below) into evaluable components. To start, the expected usage of each platform was defined in terms of its set of *mission,* as defined in the appropriate national documentation,[8] including any expectations that evolved from there, or may evolve, for their eventual replacements.[9] Next, each mission was decomposed into a set of *tasks* required to complete the mission. For example, the set of tasks for offensive missions tends to be fairly linear, following a kill chain analogy; however, tasks may also be concurrent. No mission or task prioritisation is assumed in the structure. The importance of each mission to the platform's expected usage, and the criticality of each task to the successful completion of the mission, were rated by appropriate subject matter experts (SMEs). Then, a set of *roles* that a UAV could perform in support of each platform was generated in order to assess the utility that an ideal UAV performing that role would bring to each of the platform/mission/task combinations. Finally, the ability of each UAV *type* to perform each of those roles was assessed at a high level.

The problem space decomposition described above yields a hierarchy of ratings; each level is logically combinable with the others, as shown in Figure 12.1.

<Figure 12.1 here>

The granularity at which each level of the hierarchy is defined can be varied depending on the analysis at hand; many different decompositions may arguably be suitable. In general, a good decomposition seeks to strike the appropriate balance between competing requirements at each level. Specifically, a decomposition is useful if it includes all important elements and is specific enough to distinguish between elements where appropriate, without introducing a level of detail that would make the workload unmanageable. This hierarchy was found to be granular enough to be usable and to show differences between the various options, but not so granular that it was unwieldy for the SMEs to provide all of the required ratings.

In order to ease the flow of the text, the exposition found below will focus on the fighter fleet, with appropriate MPA inclusions as necessary.

Missions and Tasks for the Fighter in the Canadian Context

In the Canadian context, the fighter[10] missions and tasks have been broadly characterised as shown below. Most of the definitions closely follow the official NATO definitions:[11]

- **Domestic Air-to-Air (A/A)**:[12] Ensure and maintain effective control over the Canadian territory, airspace, and maritime approaches including any role as defined within the NORAD agreements. The following tasks make up this mission:

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[8] Canada's MPA and fighter missions were taken from each of their statements of operational requirement and operating intent.

[9] This may seem inappropriate in light of the discussion in the Introduction regarding the fact that the manned and unmanned aircraft form a team, rather than the sum of parts. However, it was deemed acceptable at such an early stage to evaluate how the MUM-T concepts would enhance the current and planned Royal Canadian Air Force (RCAF) capability in performing its current set of missions, and how the MUM-T concepts would change the way the RCAF does business. Adding new missions to the RCAF was out of the scope of the study.

[10] No notion of how the UAV can support the fighter is assumed at this point. It is also important to remember that these are existing manned missions, and were not specifically chosen based on whether they could be enabled by using MUM-T concepts.

[11] NATO 2014.

    - **transit**: travel from the base up to the edge of the area of interest (AOI);
    - **detect**: search and detection;
    - **intercept**: closing with an entity;
    - **identify**: classification and/or identification of entities;
    - **deter**: non-lethal action(s) influencing entities;
    - **engage**: disabling of an entity; and
    - **battle Damage Assessment (BDA):** assessment of the damage to an entity after an engagement.
- **Expeditionary A/A**:[13] Comprises any situation in which the fighter force is required to deliver aerospace effects in a deployed role outside of Canada. The tasks associated with this mission are the same as for the domestic A/A mission.
- **Air-to-Ground (A/G)**:[14] Comprises any situation in which the fighter force is required to deliver ground effects.[15] The tasks associated with this mission are the same as for the domestic A/A mission.
- **Air-to-Surface (A/S)**:[16] Comprises any situation in which the fighter force is required to deliver surface effects.[17] The tasks associated with this mission are the same as for the domestic A/A mission.
- **Escort**: Involves the escort of one or more friendly unit through an area where they may be at risk. The friendly unit may be air, land or sea based. The following tasks make up this mission:
    - **transit**: from the base up to the edge of the AOI;
    - **detect**: search and detection;
    - **determine intent**: assessment of approaching entities;
    - **deter**: non-lethal action(s) influencing entities;
    - **engage**: disabling of an entity; and
    - **BDA**: Assessment of the damage to an entity after an engagement.
- **Search and Rescue (SAR)**: The SAR mission involves the fighter as either the primary SAR asset or a support to a SAR asset in the search and rescue of distressed persons. Combat SAR is out of scope in the Canadian context. The following tasks make up this mission:
    - **transit**: from the base up to the edge of the search area;
    - **detect**: search and detection;
    - **rendez-vous/track**: moving toward the unit(s) to be rescued and maintaining contact; and
    - **rescue**: picking up stranded unit(s) or dropping a SAR payload.

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[12] A/A is not an accepted NATO term, but the intent is reflected in NATO's air defence: all measures designed to nullify or reduce the effectiveness of hostile air action (NATO 2014).

[13] Ibid.

[14] A/G is not an accepted NATO term, but the intent is similar to NATO's antisurface air operation against ground, i.e., surface targets not at sea.

[15] Note that domestic A/G is not sensible outside of training or an extreme wartime context, which A/G as envisioned here would cover.

[16] A/S is not an accepted NATO term, but the intent is reflected in NATO's antisurface air operation: an air operation conducted in an air/sea environment against enemy surface forces (NATO 2014).

[17] Similar to A/G, it was felt that engagements within Canada's waters would be limited to wartime scenarios and could be considered as part of this mission.

- **Reconnaissance**: Includes the requirement to collect and transmit data on enemy or other targets of interest, including behind enemy lines. The following tasks make up this mission:
    - **transit**: transit from the base up to the edge of the AOI;
    - **data capture**: recording of sensor data;
    - **data dissemination**: sending data to another friendly unit or to headquarters; and
    - **detection avoidance**: avoiding detection by enemy units.
- **Training**: This mission includes both the fighter crew being trained, and the fighter being used in the training of another platform. It refers to improving the existing training of aircrews, not to any additional training that would be required to interact with UAVs. The general concept is that a UAV could either take the place of a (potentially more expensive or unavailable) Blue unit that the fighter needs to be able to operate with, or simulate a Red unit to provide dissimilar air combat training. The following tasks make up this mission:
    - **simulate blue**: simulate a friendly unit in a training scenario; and
    - **simulate red**: simulate a hostile unit in a training scenario.

Following the missions and tasks development, SME ratings were sought to determine the importance of each mission to the overall fighter usage and the importance of each underlying task to mission success. The ratings were then reviewed and discussed in order to obtain collective agreement. Those ratings can be found in Table (3 = critical, 2 = important, and 1 = marginal).[18]

UAV Roles

The UAV roles are defined as the possible interactions the UAV may have with the manned aircraft on a MUM-T mission. For the current case study, eight roles have been defined and have been deemed sufficient to encompass the possible interactions within the fighter mission set. The eight roles are:

1. **sensor**: acting either as an advance or complimentary sensor, feeding information to the manned aircraft that otherwise could not be obtained or which the manned aircraft does not have time to obtain;
2. **refueller (fuel)**: exchanging fuel from an aircraft containing a large amount of jet fuel, the refueller, to another aircraft while in flight;
3. **weapons delivery**: an armed UAV capable of launching ordnance at enemy units;
4. **communications relay (comms)**: a UAV serving as a node within a network for the purpose of exchanging data, information, and commands over a wireless link;
5. **decoy**: a decoy UAV is designed to attract enemy weaponry or distract the opponent’s attention in order to allow other aircraft to either proceed undetected or, at the very least, unharassed by enemy units;
6. **electronic attack (EA):** For the purposes of this study, EA is separated from the wider category of electronic warfare (specifically, electronic support measures will be considered part of the sensor role). An EA UAV emits electro-magnetic energy to

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[18] The ratings presented in Table 12.1 denote the consensus of the experts consulted during this process. For a given application of the method, a different scheme, such as averaging individual ratings, could also be employed. The authors chose consensus to stimulate discussions that would ensure that no one had mistakenly overlooked any key considerations in developing their individual ratings. For more information about missions, tasks, and associated ratings, see Arbour, Bourdon, and MacLeod (2012).

overwhelm, confuse, deceive or otherwise render ineffective the radar system of an enemy entity and/or its operator;

7. **kinetic employment (KE)**: involves the use of the UAV itself as a weapon. Note that a UAV with the sole purpose of being used kinetically is deemed to be a weapon, not a UAV. Consequently, the KE role must not be the primary role of the UAV under study; and
8. **SAR payload (SAR)**: includes a number of measures to assist the 'rescue' portion of SAR such as dropping supplies (e.g., food, medicine) or SAR technicians, possibly followed by extrication for transport to an appropriate location.

Each role can be complemented by a listing of characteristics that would need to be met by an aircraft (UAV or otherwise) performing the role. Such a list can be used to further bound the scope of the role, while also helping to determine how well each UAV type will perform the role. The SME-assessed utility of each role in each of the previously described fighter missions/task combinations is found in Table 12.1 (3 = very useful, 2 = useful, 1 = marginal, 0 – n/a).[19]

<Table 12.1 here>

It is important to note that due to the nature of the questions asked to the SMEs, the ratings found in Table 12.1 are a statement on how useful the role is in an idealised sense, i.e., in a perfect world where the role performed by a UAV would be possible. Such ratings do not take into account several factors including, but not limited to, the following:

- The existence of a manned platform already performing the role (e.g., refuelling). The fact that a manned platform is capable of performing a role, or part of a role, does not impact the usefulness of a UAV in a MUM-T context also performing that role. The costs associated with having redundant capabilities do not impact UAV utility.
- The added workload to the crew of the manned aircraft or ground-based controllers. It is understood that a pilot (or crew, for a larger aircraft) will require cognitive power to interact with an unmanned partner. Similarly, ground-based controllers will need to be dedicated to the MUM-T concept. The difficulties encountered by either do not affect the usefulness of UAVs in certain roles, as it was assumed from the onset that the appropriate level of autonomy could be achieved to alleviate those difficulties.
- Many other items such as the legalities, extra training, costs, manned aircraft modifications, etc. associated with having a UAV perform each role. These do not affect the utility of the UAV, but will certainly affect the feasibility and 'bang for the buck' of procuring such UAVs.
- The current capability of the MUM pairing in this context may lead to future research and development to add a capability, including the feasibility of incorporating UAV autonomy that is sophisticated enough to execute several complex functions.

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[19] Because every UAV role is evaluated against every task, an 'n/a' rating can be used as a valid option in cases where the role cannot support the task: it was thought that attributing a 'marginal' rating whenever the role does not have a logical place within the task would unfairly penalise the role under any rating roll-up scheme. For more information about the ratings, including a listing of the UAV characteristics that have been deemed important in support of each role, see Arbour, Bourdon and MacLeod (2012). In the missions or rating importance scale, an 'n/a' was unnecessary as the mission or task could simply be dropped from the list.

In principle, there is no reason why someone applying this method to their own problem could not take these factors into account when developing the ratings, since the ratings are an evaluation of capabilities tied to the assumptions determined at the onset of the study. Consequently, most reasonable assumptions that were clearly articulated to the SMEs prior to establishing the ratings could be incorporated into the ratings.

As noted earlier, it is clear that any one of the factors enumerated above will at the very least impact any procurement process, and in many cases affect the successful completion of a MUM-T operation. However, due to the structure of the MUAVI project under which the current case study was developed, it was deemed necessary to use the first phase of work to evaluate the utility of possible MUM-T solutions in order to reduce the problem space by taking out the lesser-valued (in a perceived utility sense) MUM pairings. Each of the factors enumerated above was to be inspected in further phases. For example, technical feasibility and the pilot workload assessment[20] was the purview of MUAVI Phase 2, while a cursory look at legal aspects[21] was done in parallel with MUAVI Phase 1.

UAV Types

For the purposes of the current analysis, a UAV has been defined as a 'powered, aerial vehicle that does not carry a human operator and can fly autonomously or be piloted remotely', with the caveat that '[a]mmunition, projectiles and missiles are not UAVs' – in accordance with the Canadian Defence Terminology Bank.

UAVs are very numerous, and assessing each individual UAV in a MUM-T context would be completely impractical. Consequently, the authors sought to group UAVs into types with similar characteristics (to parallel the description of UAV roles in which desired UAV characteristics in performing the role were originally enumerated – not shown in the present case study). However, all of the extant UAV categorisations known to the authors appeared too restrictive; some UAVs were difficult to categorise or seen as 'special cases'. Consequently, the authors designed simpler UAV groupings and avoided describing the precise delineation between each UAV type in order to avoid creating 'special cases'. Hence, the vast number of known (and possible) UAVs was categorised into six generic types, which are not explicitly defined in order to be as inclusive as possible (some UAVs may fit into more than one category):

1. **rotary wing**: for example, the Northrop Grumman MQ-8 Fire Scout and the Boeing A160 Hummingbird;
2. **fighter**: for example, unmanned versions of full-scale fighter aircraft such as the CF188 Hornet, F-35 Lightning II, and the F-22 Raptor;
3. **airliner**: for example, unmanned versions of full-scale commercial aircraft such as the Boeing 737 and military versions of similar aircraft such as the CC130 Hercules and the CP140 Aurora;
4. **high/medium altitude long endurance (HALE/MALE)**: for example, aircraft such as the General Atomics MQ-9 Reaper, the Northrop Grumman RQ-4 Global Hawk, and the CU170 Heron;
5. **airship**: for example, all lighter-than-air and hybrid aircraft such as the Lockheed Martin High Altitude Airship and Northrop Grumman's Long Endurance Multi-Intelligence Vehicle concepts; and

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[20] Pavlovic, Keefe, Fusina ND.

[21] Barrett 2012.

6. **small**: for example all tactical, mini, or micro UAVs such as the AeroVironment RQ-14 Dragon Eye, the Israel Aerospace Industries Mosquito, the CU161 Sperwer, and the CU167 Silver Fox.

In order to make an informed assessment of UAV capabilities vis-à-vis each role, a quick evaluation of each UAV type's typical capabilities was conducted using six categories: lift capacity (weight), lift capacity (size), speed, endurance, stealth, and manoeuvrability. Each UAV type is rated high, medium, or low capability for each category, as shown in Table 12.2.

<Table 12.2 here>

The UAV type characteristics as shown in Table 12.2 are typical characteristics that do not encompass any 'special case'. Using the UAV type characteristics as listed in Table 12.2 and the role definitions, each UAV type's capability to perform each role was assessed (see Table 12.3: 3 = very capable, 2 = capable and 1 = lacking).

<Table 12.3 here>

As shown in Table 12.3 through the sensor role, UAV types with very different characteristics may have been rated equally their ability to perform a specific role due to the nature of their employment: e.g., small UAVs are 'very capable' as close-up sensors, while airships are 'very capable' as persistent sensors. UAV types have thus not been penalised given the operational context in which they may perform the role; they were rated according to their expected usage in that specific role.

Data Analysis

Having gathered the necessary data, the perceived utility of UAVs in a MUM-T concept can be analysed. After each level of the problem space hierarchy (as shown in Figure 12.1) was rated by appropriate SMEs. It was then possible to 'roll up' the scores into something meaningful to the analyst and the client. For this purpose, the authors have developed the Hierarchical Prioritisation of Capabilities (HPC) method[23] allowing analysts to roll up the ratings and obtain results at any level of the hierarchy. The HPC starts with Table 12.4 as a generic representation of the rating breakdown from missions to roles. The table gives a sense of the combinatorial explosion that can be encountered if too complex a structure is adopted.

<Table 12.4 here>

To compute aggregate ratings, the ratings were converted using the exponential function in order to have differences in ratings more closely represent the order of magnitude differences that were expressed in the descriptions of each level of the rating scales. In general, this better expresses the potentially large relative qualitative differences between ratings, even between consecutive numbers. In this fashion, a rating of 2, for instance, carries a weight of a^2 while a rating of 3 has a weight equal to a^3, where a is the base for the exponential function. In order to facilitate interpretation of the results, the weighted sum is re-normalised into the same rating scheme as the inputs by using the logarithm with base a.

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[23] Bourdon, Arbour, and MacLeod 2014. A review of the HPC method closely following the work in Bourdon, Arbour, and MacLeod (2014) is presented in this section.

Given the ratings in Table 12.4 and the linkages shown in Figure 12.1, the HPC method uses hierarchical weighted sums to calculate measures of utility. The metric for the utility of role *j* in supporting mission *i* is expressed as:

$$u_{i,j} = \log_a \left(\frac{\sum_{p=1}^{n_i} a^{w_{i,p}} a^{w_{i,p,j}}}{\sum_{p=1}^{n_i} a^{w_{i,p}}} \right), \tag{1}$$

where $w_{i,p}$ is the rating of the p^{th} task relative to the i^{th} mission and $w_{i,p,j}$ is the rating of the j^{th} role relative to the p^{th} task relative to the i^{th} mission. The ratings of the importance of the task relative to the mission ($w_{i,p}$) are used as weights to better establish whether the roles can help accomplish the tasks that are the greatest contributors to the overall missions. In this manner, the formula assigns a greater score to roles that contribute at least a little to critical tasks than to roles that provide a great deal to tasks that are less important to the overall mission. This was deemed in line with operational thinking, in which the more important tasks must be performed to at least a minimum degree while lesser tasks may sometimes be omitted.

Similarly, the ratings can be aggregated one more level up the hierarchy. Specifically, when all the mission-specific ratings for a role have been computed, the overall utility of role *j* across all missions is calculated as:

$$u_j = \log_a \left(\frac{\sum_{p=1}^{M} a^{w_p} a^{u_{p,j}}}{\sum_{p=1}^{M} a^{w_p}} \right), \tag{2}$$

where the $u_{p,j}$ terms are calculated as in Equation (1) and w_p is the rating of the p^{th} mission relative to the overall set of missions. After determining each u_j, it is then possible for the analyst to determine which roles offer the greatest impact for each or all of the missions.

Given that the roles are delivered by UAV types (see Figure 12.1), it is possible to go one step further by assessing which UAV types have the greatest impact on the missions. Let's assume the generic SME ratings as shown in Table 12.5.

<Table 12.5 here>

The calculation of the rating of the utility of UAV type *l* to task *j* of mission *i* is as shown in Equation (3).

$$v_{i,j,l} = \log_a \left(\frac{\sum_{p=1, w_{i,j,p} \neq 0}^{k} a^{w_{i,j,p}} a^{x_{p,l}}}{\sum_{p=1, w_{i,j,p}}^{k} a^{w_{i,j,p}}} \right), \tag{3}$$

where $w_{i,j,p}$ is the rating of the p^{th} role relative to the j^{th} task in the context of fulfilling the i^{th} mission, and $x_{p,l}$ is the rating of the l^{th} UAV type's utility in fulfilling this role. The principal difference with previous equations is that terms that represent no utility for the role in fulfilling the task (i.e., where $w_{i,j,p} = 0$) are not included in the summation. This is to avoid penalising UAV types for not contributing a role that is not explicitly used in fulfilling the task.

From here, proceeding up the remainder of the hierarchy is much like before. The utility of a UAV type *l* in fulfilling mission *i* and across the full set of missions is given by:

$$v_{i,l} = \log_a \left(\frac{\sum_{p=1}^{n_i} a^{w_{i,p}} a^{v_{i,p,l}}}{\sum_{p=1}^{n_i} a^{w_{i,p}}} \right) \quad \text{and} \quad v_l = \log_a \left(\frac{\sum_{p=1}^{M} a^{w_p} a^{v_{p,l}}}{\sum_{p=1}^{M} a^{w_p}} \right), \tag{4}$$

respectively, where $w_{i,p}$, w_p and $v_{i,p,l}$ are defined as in Equations (1), (2), and (3). It is then possible for the analyst to determine the utility of a UAV type in fulfilling a mission or the overall set of missions.

Note that all formulae depend critically on the value of the base a. As discussed above, the choice of base allows the analyst to tailor the HPC method to the analysis at hand. While this number is difficult to precisely identify in practice, it was felt that a conservative estimate could be obtained in the context of the current case study. The authors argued that it would be reasonable to ensure that seven ratings with a value of 1 do not surpass a single rating of 3 in importance. The number seven has not been randomly chosen: given the eight fighter missions outlined earlier, it was felt that given a single 'critical' mission – or 'very important' in the case of tasks – it would take at the very least all other missions to trump that single mission in perceived utility in a particular MUM-T pairing. Mathematically, this translates into the following inequality: $7a \leq a^3$, or $a \geq \sqrt{7}$. Conversely, if enough missions or tasks have a rating of 2 ('important' or 'useful'), they should collectively become more important than a single mission or task with a rating of 3, if they are in sufficient quantity. Again, a conservative estimate is to state that a single rating of 3 should not be greater in importance than seven ratings of 2 (following a similar logic as that for the 3's versus 1's). The corresponding inequality is $a^3 \leq 7a^2$, which in turn implies that $a \leq 7$. Combining the two inequalities restricts a to the range $[\sqrt{7}, 7]$. Since the two endpoint constraints are conservative, a value near the midpoint of the interval (i.e., $a = 5$) was chosen for the original analysis.

Case Study Results Using HPC Methodology

The results of the Canadian case study for the CF188 fighter aircraft using the HPC method and the Canadian SME ratings (see Tables 12.1 and 12.2) are shown in Table 12.3 for the missions versus roles and in Table 12.4 for the missions versus UAV types.

<Table 12.6 here>

<Table 12.7 here>

As can be seen, the sensor role has the highest expected overall utility by a wide margin. The decoy and EA roles are second – keeping in mind that 0.4 is a large gap on the logarithmic scale with base 5 used. Niche roles that are well suited only for some missions can also be seen: for example, the decoy role for the A/G mission and the refueller for the reconnaissance mission.

Higher UAV type usefulness can be seen in the Airliner UAV – potentially a nod to the versatility of the current generation of these manned aircraft and their capability to take on many different payloads. The fighter type falls in second place, due to its commonality with the current Canadian fighter and its logical place as a wingman, the HALE/MALE, due to the significant existing developments and the small type due to the potential for niche capabilities. Finally, the rotary wing UAV appears to be the least desirable as a complement to the Canadian fighter, potentially due to its slow speed and overt usage, compared to the small type with its slow speed and covert usage.

As an aside, the MPA analysis also showed that the sensor role scores much higher than the other roles, so much so that limited utility can be seen from the other roles in an overall sense. This result has been attributed to the assumed capability of the MPA to take on additional payloads and operators, thus minimising the need for a complementary platform. The problem as formulated by the client in this case was to look at how UAVs may complement existing platforms, but this result in itself suggests the limitations of setting aircraft requirements independently rather than with a team concept in mind. The utility of roles to missions is highest (although not particularly high in absolute terms) for the various patrol missions (i.e., anti-surface warfare patrol, anti-submarine warfare patrol, and land patrol). However, in general the utility is higher for the UAVs when coupled with the fighter than it is for the MPA, owing to the fighter's much more specialised role.

Case Study Observations

A list of trends, or specific results, of note from the original Canadian case study[24] is found below.

- The consistently high rating of sensor marks is a very important role in support of both MPA and fighter. This is not particularly surprising, as it is really an enabler for every other mission.
- Other than sensor, none of the roles appeared especially relevant to the MPA. This is partially the case because the study looked only at cases in which the UAV would be used in concert with the MPA – whereas in many cases a UAV would be most applicable as a full-up replacement or alternative to the MPA.
- The decoy and EA roles appear to be a favourable option for pairing with the fighter. It should be noted that the expeditionary capabilities of the fighter force (to which these roles are applicable) are very important, but are not used that frequently. Both roles have their highest rating for training, allowing them to be useful during peacetime. The decoy role is also equally useful in an A/G capacity.
- The airliner type looks to be very broadly applicable, as it strikes a good balance of capabilities. This is perhaps not surprising, given the number of variants of, for example, the Lockheed CC130 Hercules currently in service.
- HALE/MALE aircraft appear quite capable, which is perhaps not entirely surprising given the research and development effort that has been expended in developing off-the-shelf models.
- From the data presented in Tables 12.1 and 12.6, niche UAV roles can be deduced such as SAR payload supporting a SAR mission, refueller supporting a transit task, weapons delivery supporting an engage task, etc.[25] More specialised niche roles can also be envisaged such as communications relay in the Arctic region – although this conclusion needs the extra assumption (not presented in this chapter) that extra communications relay are necessary in the Canadian Arctic.

Interactions and Autonomy Considerations

Although the case study revealed interesting MUM-T combinations, the decision regarding which MUM pairing to pursue through acquisition is far from easy to make. The results of the Canadian case study (as shown in Tables 12.6 and 12.7 and in the Observations section above) highlight some key pairings with high perceived utility, but, as alluded to in the previous sections, high utility does not necessarily translate into the highest return on investment due to other constraints that must also be analysed. As the current case study

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[24] Arbour, Bourdon, and MacLeod 2012.

[25] Note that although obvious, any legitimate method must have these results rise to the top by the sheer nature of their links to specific tasks.

looks at UAV capabilities in a MUM-T context, it is natural to leave any notions of costs and technical feasibility aside. However, UAV utility in a MUM formation is not solely determined by SME ratings and an HPC analysis.

Although the SME ratings found herein were produced under the assumption that an ideal UAV exists for the job being rated, no explicit discussion of how the MUM-T mission would be carried out occurred that renders the notion of 'ideal' fuzzy. As with any teaming efforts involving humans, determining the relationship and interactions between the parts (as well as the level of autonomy given to each part) will play a large role in the team's success in achieving its goal. In a man-machine teaming, these notions are magnified as they must be defined from the onset in order to ensure that proper failsafe mechanisms are implemented, which implies that changes cannot be made on the fly to correct a teaming arrangement that has been deemed non-optimal for the situation: e.g., too little UAV autonomy might burden the manned crews, while too much autonomy may produce unpredictable behaviour that may limit the UAV's usage in critical situations.

In order to be successful, a MUM team must act as one system in pursuit of its goal. Within this system, the interactions between the manned and the unmanned aircraft must be well defined in order to task each element appropriately and in order to pre-program the necessary elements in the UAV's software. The NATO STANAG 4586[26] offers five agreed-upon levels of interoperability (LOIs)[27] that characterise the type of interaction the manned aircraft may have with the UAV:

- Level 1: indirect receipt and/or transmission of sensor product and associated metadata, for example key length value metadata elements from the UAV;
- Level 2: direct receipt of sensor product data and associated metadata from the UAV;
- Level 3: control and monitoring of the UAV payload unless specified as monitor only;
- Level 4: control and monitoring of the UAV, unless specified as monitor only, less launch and recovery; and
- Level 5: control and monitoring of UAV launch and recovery unless specified as monitor only.

As discussed in the Introduction, UAVs and manned aircraft currently fly within the same airspace, but only on rare occasions would they directly influence each other's action: a UAV gets imagery that, once dissected by imagery specialists, is redirected to the proper manned platform for action (LOI 1).

Although the Canadian case study has found that a Sensor UAV in support of a fighter performing an A/G patrol is very useful, using different LOI between the UAV and the fighter will cause the mission to unfold differently. Having the ability to monitor a UAV's payload in real time can allow the fighter to react more quickly than it otherwise would be capable of. By further having control of the UAV or its payload, the fighter can ensure the UAV will offer the imagery needed by the pilot without going through a third-party operator, which may introduce lag or errors in the system. However, increasing the LOI level, which may at first glance appear like the best thing to do, need not be a positive option:

- LOI 1: The fighter could be waiting to receive critical imagery from the UAV, or could see the UAV operators not respond to a request for specific imagery. This could easily result in mission failure.

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[26] NATO 2012.

[27] Unless otherwise stated, LOI 3, 4, and 5 assume control and monitor.

- LOI 2: The fighter could see the UAV operators not respond to a request for specific imagery. Since the fighter need not wait to receive imagery; Level 2 may see an increase in mission success over level 1, but may still result in mission failure if specific requests are not met in a timely manner.
- LOI 3: The fighter will request and receive the necessary imagery from the UAV. This is the best-case scenario.
- LOI 4: The fighter will request and receive the necessary imagery from the UAV. However, the cognitive demands of flying the UAV may surpass the limits of the pilot's abilities. This may end up in mission failure.
- LOI 5: This is a more extreme case than level 4 and may also end up in mission failure.

The fighter's MUM-T A/G patrol LOI narrative – and the other missions' narratives that may end up with different conclusions for some LOIs – highlights the importance of defining the teaming arrangements ahead of developing a MUM team. Pairing the current manned platforms with high TRL UAVs designed as stand-alone systems evidently contradicts this conclusion.

There are many factors contributing to the continuing long tradition of avoiding a full evaluation of the MUM-T concepts. For one, the ease of simply adding a UAV to the battlefield and the success stories associated with LOI 1 – as opposed to not fielding UAVs, a sort of undefined LOI 0 – may convince decision makers that a solution has been found and the problem resolved. This may be inflated by the failure of fleet planning mechanisms, such as the capability-based planning previously discussed, to properly evaluate MUM-T capabilities that represent more than the sum of the parts. Or the costs and delays associated with the design, development, and acquisition of both manned and unmanned platform teams may appear unacceptable.

By failing to evaluate the gains provided by defining proper MUM-T arrangements, decision makers not only minimise the potential for extra gains in mission success but also disregard any impact on the fleets' mission set. The current problem's setup (looking at improvements in the current manned aircraft's mission set) or its extension (looking at improvements in the current unmanned missions set) will lead to finding optimal aircraft pairings only. However, missions that are currently impossible with the manned or unmanned fleets may be possible using MUM-T concepts through the use of one aircraft to offset the other's limitations. Such a concept has already been discussed in the introduction as the reason for the influx of UAVs – along with the necessary LOI 1 – in the battlefield. However, pushing this notion further could open up many more opportunities that could influence how conflicts are fought and won: novel usage of assets may increase mission success, which in turn may shorten conflicts and decrease human casualties.

Conclusion

While utility, and interest, has been shown for the MUM-T concept in the Canadian context, understanding the proper teaming arrangements – such as the proper LOI and necessary UAV autonomy for the mission at hand – is still lacking. This situation has many roots. During ongoing conflicts there can be a real or perceived need to rapidly acquire and deploy forces, with an attendant default to C/MOTS options. While at least in the medium term it is inevitable that one or the other of the manned or unmanned aircraft will be a legacy fleet, which constrains the options, there is an opportunity to consider the broader applicability and potential of new acquisitions. There is also an opportunity for researchers and industry to look more broadly with their programmes, so that more generally useful unmanned aircraft are available as C/MOTS when the next acquisition cycle arises. In any event, fighting the next war with today's assets cannot reliably ensure future successes. MUM-T should be developed – or at least planned – as a system, rather than assembled parts, in order to develop the proper synergies and ensure the appropriate teaming arrangements. Failing this, an increase in mission success may occur, but at a much slower rate. Finally, the case study described herein followed a set of assumptions that could be changed in order to expand the problem space and assess the greater use of unmanned aircraft, such as evaluating the use of manned aircraft in support of unmanned missions or even assessing the MUM-T concept for missions that cannot currently be performed by either manned or unmanned aircraft. Moreover, such assessments of utility need not be limited to air systems: unmanned systems teaming with manned land or maritime platforms can use similar techniques and arguments to maximise the long-term utility of the proposed MUM-T.[28]

References

Arbour, Benoît, Bourdon, Sean, and MacLeod, Matthew R. *Manned-Unmanned Aerial Vehicle Interactions Phase 1: Preliminary Concept Assessment*. DRDC CORA TM 2012-028. Ottawa: Defence Research and Development Canada, 2012.

Barrett, Carrie. UAV Regulations Survey. Contract Report, DRDC CORA CR 2012-102, Defence Research and Development Canada, 2012.

Bourdon, Sean, Arbour, Benoît, and MacLeod, Matthew R. 'A Method for Hierarchically Prioritizing Capabilities with an Application to Military Manned and Unmanned Aerial Vehicles'. *Journal of Applied Operational Research* 6/1 (2014):39–47.

Haché, Chris. Maritime Remote Autonomous Systems Concept Development: MRAS Threats Workshop Quick-Look Report. Halifax, Nova Scotia: Canadian Forces Maritime Warfare Centre, 2013.

National Defence and the Canadian Armed Forces. Completed Access to Information Requests 2014. Available at http://www.forces.gc.ca/en/transparency-access-info-privacy/2014-completed-requests.page, accessed 14 August 2014.

North Atlantic Treaty Organization (NATO). NATO Glossary of Terms and Definitions (English and French). AAP-06, 2014.

North Atlantic Treaty Organization (NATO). *STANAG 4586 Navy (Edition 3) - Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability*. 9 November 2012.

Pavlovic, Nada J., Keefe, Alan, and Fusina, Giovanni. 'Human Factors Issues in Airborne Control of Multiple Unmanned Aerial Vehicles'. DRDC Toronto TM 2013-098, Defence Research and Development Canada, Unpublished.

US Department of Defense (DOD). *Unmanned Systems Integrated Roadmap: FY2013 - 2038*. 2013.

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[28] See, e.g., Haché 2013.

Table 12.1. Canadian Fighter Missions, Tasks and Roles SME Ratings

Mission (Importance Rating)	Task (Importance Rating)	Sensor	Fuel	WD	Comms	Decoy	EA	KE	SAR
Domestic A/A (3)	Transit (3)	1	3	0	2	0	0	0	0
	Detect (3)	3	2	0	1	1	0	0	0
	Intercept (3)	2	0	0	1	0	0	0	0
	Identify (3)	3	0	0	2	0	0	0	0
	Deter (3)	2	0	3	2	3	3	2	0
	Engage (3)	3	0	3	3	2	2	2	0
	BDA (2)	3	1	0	3	2	0	0	0
Expeditionary A/A (3)	Transit (3)	2	3	0	2	2	0	0	0
	Detect (3)	3	2	0	1	1	0	0	0
	Intercept (3)	2	0	0	1	2	2	0	0
	Identify (3)	3	0	0	2	1	0	0	0
	Deter (3)	2	0	3	2	3	3	1	0
	Engage (3)	3	0	3	3	2	3	2	0
	BDA (2)	3	1	0	3	2	0	0	0
A/G (3)	Transit (3)	2	3	0	2	2	0	0	0
	Detect (3)	3	2	0	1	3	0	0	0
	Intercept (3)	2	0	0	1	2	2	0	0
	Identify (3)	3	0	0	2	3	0	0	0
	Deter (3)	2	0	3	2	3	3	2	0
	Engage (3)	3	0	3	3	2	3	2	0
	BDA (2)	3	1	0	3	2	0	0	0
A/S (2)	Transit (3)	2	3	0	2	1	0	0	0
	Detect (3)	3	2	0	1	1	0	0	0
	Intercept (3)	2	0	0	1	1	2	0	0
	Identify (3)	3	0	0	2	1	0	0	0
	Deter (3)	2	0	3	2	3	3	1	0
	Engage (3)	3	0	3	3	3	3	2	0
	BDA (2)	3	1	0	3	3	0	0	0
Escort (2)	Transit (3)	3	3	0	2	2	2	0	0
	Detect (3)	3	2	0	1	1	0	0	0
	Determine Intent (3)	2	0	0	2	1	0	0	0
	Deter (3)	2	0	3	2	2	3	1	0
	Engage (3)	3	0	3	3	2	3	2	0
	BDA (2)	3	0	0	3	2	0	0	0
SAR (1)	Transit (3)	1	3	0	2	0	0	0	0
	Detect (3)	3	2	0	3	0	0	0	0
	Rendez-vous (3)	1	0	0	1	0	0	0	0
	Rescue (3)	3	0	0	2	0	0	0	3
Reconnaissance (2)	Transit (3)	2	3	0	2	0	0	0	0
	Data Capture (3)	3	2	0	2	1	0	0	0
	Data Dissemination (3)	0	0	0	3	0	0	0	0
	Detection Avoidance (2)	3	0	0	2	2	0	0	0
Training (3)	Simulate Blue (3)	3	2	0	1	3	2	0	0

Simulate Red (3)	3	2	1	1	2	3	0	0

Table 12.2. UAV Capabilities

	Rotary Wing	**Fighter**	**Airliner**	**HALE/ MALE**	**Airship**	**Small**
Lift Capacity (Weight)	Medium	High	High	Low	High	Low
Lift Capacity (Size)	Medium	Medium	High	Low	High	Low
Speed	Low	High	Medium	Medium	Low	Low
Endurance	Low	Low	Medium	High	High	Low
Stealth	Low	Medium	Low	Medium	Low	High
Manoeuvrability	Medium	High	Medium	Medium	Low	Medium

Table 12.3. UAV Type against each Role Rating

	Rotary Wing	Fighter	Airliner	HALE/ MALE	Airship	Small
Sensor	2	3	3	3	3	3
Refueller	1	2	3	1	1	1
Weapons Delivery	2	3	3	3	2	1
Comms Relay	2	2	3	2	2	1
Decoy	2	3	3	3	1	3
EA	1	3	3	3	2	3
Kinetic Employment	2	3	3	2	1	2
SAR Payload	3	1	2	1	2	1

Table 12.4. Ratings for Roles Relative to Manned Aircraft Missions

Mission Name	Mission Rating	Task Name	Task Rating	Utility Rating		
				Role 1	…	Role k
A	w_1	A$_1$	$w_{1,1}$	$w_{1,1,1}$		$w_{1,1,k}$
		...	…	…	…	…
		An_1	w_{1,n_1}	$w_{1,n_1,1}$		$w_{1,n_1,k}$
B	w_2	B$_1$	$w_{2,1}$	$w_{2,1,1}$		$w_{2,1,k}$
		...	…	…	…	…
		Bn_2	w_{2,n_2}	$w_{2,n_2,1}$		$w_{2,n_2,k}$
…	…	…	…	…	…	…
M	w_M	M$_1$	$w_{M,1}$	$w_{M,1,1}$		$w_{M,1,k}$
		...	…	…	…	…
		Mn_M	w_{M,n_M}	$w_{M,n_M,1}$		$w_{M,n_M,k}$

Table 12.5. Ratings of UAV Types in Fulfilling Specific Roles

	UAV Type			
	Type 1	Type 2	…	Type *m*
Role1	$x_{1,1}$	$x_{1,2}$	…	$x_{1,m}$
Role 2	$x_{2,1}$	$x_{2,2}$	…	$x_{2,m}$
…	…	…	…	…
Role *k*	$x_{k,1}$	$x_{k,2}$	…	$x_{k,m}$

Table 12.6. Overall rating of UAV Roles against Canadian Fighter Missions

Mission	**Sensor**	**Fuel**	**WD**	**Comms**	**Decoy**	**EA**	**KE**	**SAR**
Domestic A/A	2.7	2.0	2.0	2.3	2.3	2.0	1.3	0.0
Expeditionary A/A	2.7	2.0	2.3	2.3	2.2	2.4	1.1	0.0
A/G	2.7	2.0	2.3	2.3	2.7	2.4	1.3	0.0
A/S	2.7	2.0	2.3	2.3	2.4	2.4	1.1	0.0
Escort	2.8	2.1	2.4	2.4	1.8	2.5	1.2	0.0
SAR	2.6	2.3	0.0	2.4	0.0	0.0	0.0	2.2
Reconnaissance	2.5	2.4	0.0	2.5	0.8	0.0	0.0	0.0
Training	3.0	2.0	0.7	1.0	2.7	2.7	0.0	0.0
Overall	2.8	2.0	2.1	2.2	2.4	2.4	1.1	0.1

Table 12.7. UAV Ratings against Canadian Fighter Missions

	Rotary Wing	**Fighter**	**Airliner**	**HALE/ MALE**	**Airship**	**Small**
Domestic A/A	1.9	2.8	3.0	2.8	2.6	2.7
Expeditionary A/A	1.9	2.9	3.0	2.8	2.5	2.8
A/G	1.9	2.9	3.0	2.9	2.4	2.8
A/S	1.8	2.9	3.0	2.8	2.5	2.8
Escort	1.9	2.8	3.0	2.8	2.5	2.7
SAR	2.2	2.5	2.9	2.5	2.5	2.4
Reconnaissance	1.9	2.5	3.0	2.5	2.4	2.3
Training	1.8	2.9	3.0	2.9	2.5	2.9
Overall	1.9	2.9	3.0	2.8	2.5	2.8