Evaluation of an Interoperable Vertical Take-Off Unmanned Aerial Vehicle for Operations with Unmanned Ground Vehicles

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Abstract: The ongoing global military operations and related defence research have placed emphasis on future conflict environments from a complex terrain/urban perspective, including threats from Improvised Explosive Devices (IEDs). Conventional countermine equipments and doctrines needs to be re-considered for the development of a new operational philosophy from an unmanned technology perspective. The Sir Lawrence Wackett Centre for Aerospace Design Technology has embarked on investigations and conceptual design studies of an interoperable VTUAV for IED detection operations with UGVs.

The conceptual design under development at the Wackett Centre is evaluated based on the Analytical Hierarchy Process. The decision criteria by which the design is evaluated measures the overall mission effectiveness of the system, in comparison to a platform centric system, for countermine/IED detection operations. Having evaluated the benefit of the interoperable design, the process is flexible to incorporate additional network centric alternatives for comparison; suitable in optimising the design.

1. INTRODUCTION

Traditional countermine operations are conducted in open, simple, and predictable terrain by qualified military personnel and combat engineers. Recent conflicts and present army research have placed emphasis to address future conflict environments from a complex terrain/urban perspective, including additional threats from Improvised Explosive Devices (IEDs). The complex urban environment places transition challenges on the present countermine techniques and doctrines for application in futuristic requirements. Some conventional countermine equipment are also ineffective in the new terrain environment and application of unmanned technology and its operational philosophy needs to be considered [1-3].

This research paper evaluates the effectiveness of Vertical Take-off Unmanned Aerial Vehicle (iVTUAV), interoperating with Unmanned Ground Vehicles (UGVs), to conduct countermine/IED detection operations. The investigation involves a comparative analysis of the mission effectiveness of network-centric system design to a platform-centric system design using the Analytical Hierarchy Process (AHP).

2. ANALYTICAL HIERARCHY PROCESS

The Analytical Hierarchy Process (AHP) solves multi-criteria decision making problems by explicit logical analysis to select the most optimum solution. The AHP concept comprises of three principles [4]:

Structuring Hierarchies: A functional hierarchy is constructed to decompose the complex system into constituent parts according to their essential relationships. At the top level of the hierarchy is the focus of the problem. Subsequent levels host the decision criteria, with several sub-criteria. The last level of the hierarchy is formed by the alternative solutions, linked to the decision criteria on which it will be judged.

Setting Priorities: The subsequent principle of the process involves analysing the priorities of elements in the hierarchy in terms of their contribution to the focus of the hierarchy. Priority analysis is carried out by making pairwise comparison, i.e. compare the elements in pairs against a given criterion in a matrix format, to evaluate local "Vector-of-Priorities". The qualitative judgements are converted into quantitative values based on a scale of 1-9, as follows: (a) 1 – equal importance; (b) 3 – moderate importance; (c) 5 – strong importance; (d) 7 – very strong importance; (e) 9 – extreme importance; and (f) 2, 4, 6, 8 – intermediate values between two adjacent judgements. The Vector-of-Priorities are then synthesised to yield a global Overall Vector of Priority that ranks the alternatives.

Logical Consistency: The third principle evaluates the consistency of the matrices. The intensities of the judgements of relations among the elements are based on a particular criterion to justify the logic. Inconsistencies in the matrices will require review of judgements.

3. ALTERNATIVE SOLUTIONS

The AHP evaluation will compare two alternatives, a network-centric system and a platform-centric system for the stipulated requirement of countermine/IED detection operations.

Operational Concept 1 (OC1): It is a network-centric system designed utilising the interoperable design methodology [5-7]. The system consists of an interoperable VTUAV capable of transporting two UGVs to the target area. The iVTUAV and UGV conduct collaborative IED countermine operations. The iVTUAV provides wide area coverage while the UGVs provides precise detection, and target manipulation and inspection capabilities. The operational concept is illustrated in Figure 1.

Operational Concept 2 (OC2): It is a platform-centric system designed utilising traditional rotary wing design methodology [8]. The system consists of a VTUAV conducting wide area IED countermine operations as a single system. The operational concept is illustrated in Figure 2.

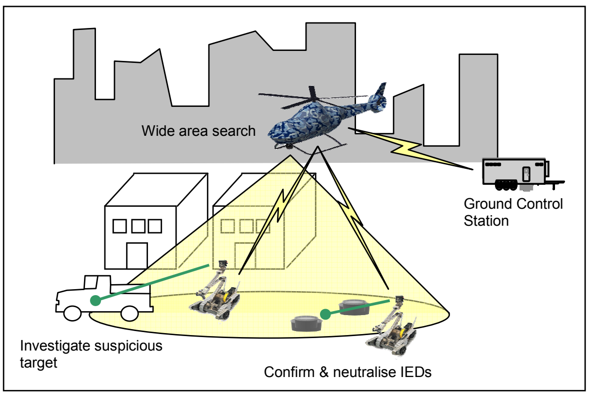


Figure 1: Operational Concept 1

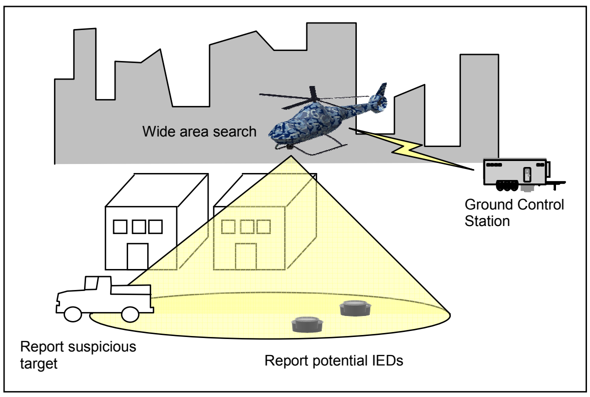


Figure 2: Operational Concept 2

4. DECISION CRITERIA

The AHP evaluation will compare two alternatives against various decision criterions that evaluate the 'Overall Mission Effectiveness' (OME) of the systems for the stipulated requirement of countermine/IED detection. To evaluate helicopter system effectiveness holistically [9], the design parameters that need to be considered are; (a) mission capability; (b) flight performance; (c) system reliability; (d) system maintainability; and (e) cost.

Since these parameters were originally conceived for a traditional platform centric helicopter system, it is modified to incorporate the system-of-system concept of NCW which is required for OC1. 'Flight performance', being an individual system performance parameter, is not of relevance when comparing system-of-systems performances. 'Mission capability' is analysed as 'IED countermine effectiveness', and 'survivability' is considered separately to reflect the specific operational defensive requirements of countermine in a hostile environment. Cost, not being an applicable measure of Overall Mission Effectiveness, is subsequently considered for cost effectiveness analysis.

4.1 IED Countermine Effectiveness

Several parameters contribute to IED countermine effectiveness. Only measurable parameters are considered for illustration. Considering the operational need for IED detection and neutralisation, the parameters considered are the following (a) mission area coverage; (b) localisation accuracy; (c) confirmation capability; and (d) neutralisation capability.

4.1.1 Mission Area Coverage

The mission area coverage is the amount of area a system 'covers', or in this case study, searches for IEDs at a stipulated point-of-time and is evaluated from the following [10];

$$A = V \times W \times t \quad (1)$$

where,

A = area coverage; V = velocity of system;

t = search time; and W = observation width/sensor swath.

As the operational requirements stipulate an urban environment, the search area of an airborne platform is limited by buildings, vehicles, etc. The area coverage of a ground platform is assumed unaffected due to the capability of searching within, and under many of these objects.

A system-of-systems total area coverage is the aggregate of all area covered by all platforms, with no duplication of areas covered by multiple platforms. Thus, for OC1, the total area covered comprises of iVTUAV and UGV coverage, and is evaluated from the following;

$$TAC = A_{UAV} \quad \text{when } A_O \leq A_{UGV} < A_{UAV} \quad (2)$$

$$TAC = A_{UAV} - A_O + A_{UGV} \quad \text{when } A_{UGV} < A_O < A_{UAV} \quad (3)$$

$$TAC = A_{UGV} \quad \text{when } A_{UGV} < A_{UAV} \leq A_O \quad (4)$$

where,

TAC = total area coverage; A_{UAV} = area coverage of VTUAV;

A_{UGV} = area coverage of UGVs; and A_O = total obstructed area.

Since OC2 is a platform centric design, total area coverage is only the area covered by the VTUAV and is evaluated from the following;

$$TAC = A_{UAV} - A_O \quad \text{when } A_O < A_{UAV} \tag{5}$$

$$TAC = 0 \quad \text{when } A_{UAV} \leq A_O \tag{6}$$

The velocity of the airborne platforms is as stipulated in the mission requirements and achieved in the design, while the velocity of the ground platforms is pre-set being off-the-shelf procurement. Search time for both platforms is stipulated in the mission requirements. The observation width, or sensor swath, is estimated [11] as follows, being proprietary data;

$$W = 0.68 \times D \tag{7}$$

where,
W = observation width/sensor swath; and D = distance

Distance for the airborne platform is taken as the VTUAV's operational altitude, as defined in the design requirements. The ground platform's sensor range is estimated as 50 metres for illustration.

The total area coverage of OC1 and OC2 is plotted as a function of total obstructed area and used for comparison to evaluate local vector of priorities for the AHP.

4.1.2 Localisation Accuracy

Localisation accuracy measures the degree-of-accuracy of a sensor in determining target location, in a cluttered environment. Gaussian distribution can provide a probabilistic representation of target location. Multi-sensor data fusion enhances the degree-of-accuracy. Fusion of multi-sensor based measurements can be achieved by adopting occupancy grid Bayesian framework based on Independent Opinion Pool [12, 13].

The Independent Opinion method does not provide any decision support on disparate measurements [13]. Thus, taking into account sensor certainty and reliability in a Bayesian framework, the Gaussian distribution of data fusion measurements is expressed as follows [13];

$$p(x \mid z_1, \ldots z_n) = \frac{1}{\sigma_{Fus}\sqrt{2\pi}} e^{\left\{\frac{-(x - z_{Fus})^2}{2\sigma^2}\right\}} \tag{8}$$

where,
$p(x|z_1,\ldots z_n)$ = fused probability σ_{Fus} = measure of fused data uncertainty;
z_{Fus} = fused expected target location; and x = location points

where,

$$\sigma_{Fus}^2 = \left[\sum_{i=1}^{n} \left(\sigma_i^{-2}\right)\right]^{-1} \tag{9}$$

$$z_{Fus} = \arg\max\left[\frac{1}{\left(\prod_{i=1}^{n}\sigma_i\right)\sqrt{2\pi}} e^{-\left\{\sum_{i=1}^{n}\left(\frac{(x-z_i)^2}{2\sigma_i^2}\right)\right\}}\right] \tag{10}$$

Since real models of sensor uncertainties are commercial-in-confidence, to illustrate, it is assumed the airborne sensor (for both OC1 and OC2) follows a normal distribution (i.e. $\sigma = 1$) while the ground sensors (for OC1) are with low accuracy (i.e. $\sigma = 2$).

The probabilistic nature of localisation accuracy imposes random measurements of detections. Hence, a wide range is investigated as case studies. Comparative analysis of OC1 and OC2 is accomplished by analysing their respective distributions of cases. The distribution for OC1 is the total probability distributions of the airborne and ground sensors, while the distribution for OC2 is the probability distribution of the airborne sensor. Based on this analysis, local vector of priorities are evaluated for the AHP.

4.1.3 Confirmation Capability

Suspected objects detected by sensors need to be confirmed as mines/IEDs. A cluttered environment leads to false alarms which hinders the effectiveness of an operation. Current technologies are limited with no technology effective in all settings. Field testing and technology demonstrations are effective in measuring the performance of a system in detecting and confirming targets [14, 15].

As the alternative designs are still in their preliminary phases, premature measurement of the confirmation capability can be estimated based on an assessment matrix where confirmation is dependent on the following: a) false alarm rate of the sensor; b) the systems inspection distance; and c) capability to probe/manipulate the area/object of interest. The system in consideration is allocated scores based on these parameters. The total score is a measure of the confirmation capability. The confirmation capability of OC1 and OC2 is estimated using an assessment matrix for comparison, to evaluate local vector of priorities for the AHP. Real values of sensor false-alarm rates are proprietary data. Hence, in the payload design, it is assumed equal for both OC1 and OC2.

4.1.4 Neutralisation Capability

Once detected and confirmed, an IED is to be neutralised. This requires Explosive Ordnance Disposal (EOD) tools which include various defensive systems such as disrupters and breaching tools, and miscellaneous mission systems such as manipulators and grippers [6]. To evaluate the neutralisation capability, the number of defensive systems and miscellaneous systems in the payload that contribute to EOD are considered. This is used for comparison, to evaluate local vector of priorities for the AHP.

4.2 Survivability

Survivability is defined as a balance of CONOPS & tactics, technology, and cost for a given threat. Some of the key parameters [16] that contribute to survivability are (a) situational awareness; (b) stand-off range; (c) signature reduction; and (d) countermeasures.

4.2.1 Situational Awareness

Information sharing and situational awareness amongst systems in a network enables collaboration and self-synchronisation, to enhance survivability [17, 18]. The degree of situational awareness is estimated by an assessment matrix which includes the following: a) number of systems integrated in the network; b) number of times the communication occurs across systems; and c) importance of the data in enhancing survivability. The system in consideration is allocated scores based on these parameters. The total score is a measure of the degree of situational awareness. Since the parameters vary from one sortie to the next, a typical sortie is considered for the system in consideration. The degree of situational awareness of OC1 and OC2 is estimated using an assessment matrix for comparison, to evaluate local vector of priorities for the AHP.

4.2.2 Stand-Off Range

Stand-off range is the distance that a system can effectively operate while still being beyond the effective range of hostile threats. Greater standoff ranges provide increased survivability [16]. In this case study, since OC1 and OC2 will operate in the same environment present with the same threats, the stand-off range is simply measured as the operating altitude of the VTUAVs, where a higher altitude provides greater survivability.

Generally, UAV operating altitudes can be classified as low (below 10,000 ft), medium (10,000-30,000 ft), and high (above 25,000 ft). Since shoulder launched IR missiles, the greatest ranged threat from insurgents, is capable of reaching medium altitudes, comparison of altitudes is more significant based on altitude classification, rather than marginal differences within each classification [16]. The operating altitudes of OC1 and OC2, defined in the design requirements, are compared, to evaluate local vector of priorities for the AHP.

4.2.3 Signature

Signature reduction measures enhances survivability by making it difficult for the adversary to detect the system and if detected, making it difficult for the adversary to successfully hit the system upon being fired on [8]. Considering the general unsophistication of insurgent technology, the most significant signature parameters to be considered are; (a) visual; (b) noise (acoustic); and (c) heat to counter IR missiles.

Visual: A suitable metric for visual signature is the systems physical size, where a smaller VTUAV provides greater survivability. Generally, UAVs are classified as micro, small, medium, and large based on its maximum take-off weight, wingspan, operating altitude, and speed [16, 19]. Comparison of size is more significant based on size classification, rather than marginal differences within each classification but should still be considered. The sizes of the VTUAVs in OC1 and OC2 are compared, to evaluate local vector of priorities for the AHP.

Noise: The main contributors to noise are the powerplant, and rotors. The acoustic signature is estimated based on an assessment matrix which includes the following: a) the type of powerplant (for example, electric power systems offer lower noise signatures), b) if the powerplant is 'buried' which dampens noise levels; c) the tip speed and the tip shape of the rotors, where lower tip speeds and non-squared tip shapes lower noise signatures; and d) the use of the NOTAR anti-torque system as opposed to the conventional tail rotor as it provides a large reduction in tail rotor noise [8, 16, 20]. The system in consideration is allocated scores based on these parameters. The total score is a measure of the noise signature. The noise signature of the VTUAVs in OC1 and OC2 is estimated using an assessment matrix for comparison, to evaluate local vector of priorities for the AHP.

Heat: The major source of heat is the propulsion subsystem of the VTUAV. The heat signature is estimated based on an assessment matrix which includes the following: a) utilising mufflers; b) utilising heat-absorbing materials; and c) utilising cold air mixing to reduce heat from the engine exhaust. While air friction creates heat on leading edges of an aircraft, a significant heat signature occurs only at very high speeds and thus is not considered for this case study [21, 22]. The system in consideration is allocated scores based on these parameters. The total score is a measure of the heat signature. The heat signature of the VTUAVs in OC1 and OC2 is estimated using an assessment matrix for comparison, to evaluate local vector of priorities for the AHP.

4.2.4 Countermeasures

Active countermeasures such as warning sensors (radar, laser, and missile), jammers (radar and infrared), and chaff and flare dispensers enhance survivability by countering the threat of missile fire [8, 23]. Contribution to survivability from a system's countermeasures is measured by the number of defensive systems in the payload design and their effectiveness in countering the threat identified in the operational environment. The survivability contribution from the countermeasures of the VTUAVs in OC1 and OC2 is estimated, given the threat includes insurgent IR missiles. The estimates are then used for comparison, to evaluate local vector of priorities for the AHP.

4.3 System Reliability

Reliability is the probability that a system will perform in a satisfactory manner for a given period of time when used under specified operating conditions, and can be measured by the failure rate of the system from the following [9, 10];

$$R(t) = e^{-\lambda t} \tag{11}$$

where,

R(t) = reliability function, λ = failure rate; and t = possible down-time

Assuming exponential distribution, reliability can be defined as the system 'mean time between failure' (MTBF);

$$MTBF = \frac{1}{\lambda} \tag{12}$$

The reliability of the total system is governed by the individual subsystem reliabilities in a network construct. The network construct can be; (a) series in which all components in the system must operate successfully in order for the whole system to operate successfully; (b) parallel if only one component needs to operate successfully for the whole system to operate successfully; and (c) combined in which the components are combined partly in series and partly in parallel. The network construct is represented using a reliability block diagram of the connections between subsystems. The system operates successfully if there is an uninterrupted path between input and output in the network. The equations to calculate reliability of block diagrams in various networks are as follows [9, 10];

$$R_{S(Series)} = \prod_{i=1}^{n} R_i \tag{13}$$

$$R_{S(Parallel)} = 1 - \prod_{i=1}^{n} (1 - R_i) \quad (14)$$

where,
R_S = overall system reliability; and R_i = subsystem reliability.

The subsystems, or mission systems, as identified in the structural hierarchy [6] were categorised into six components. The total system reliability of OC1 and OC2 can be evaluated by constructing these six mission system components in a functioning sequence, based on their activities to meet the mission requirements, in a reliability block diagram and using the expressions above to find the MTBF. The MTBF of the alternatives is then used for comparison, to evaluate local vector of priorities for the AHP. As an illustration, the reliability block diagram of OC1 is presented in Figure 3.

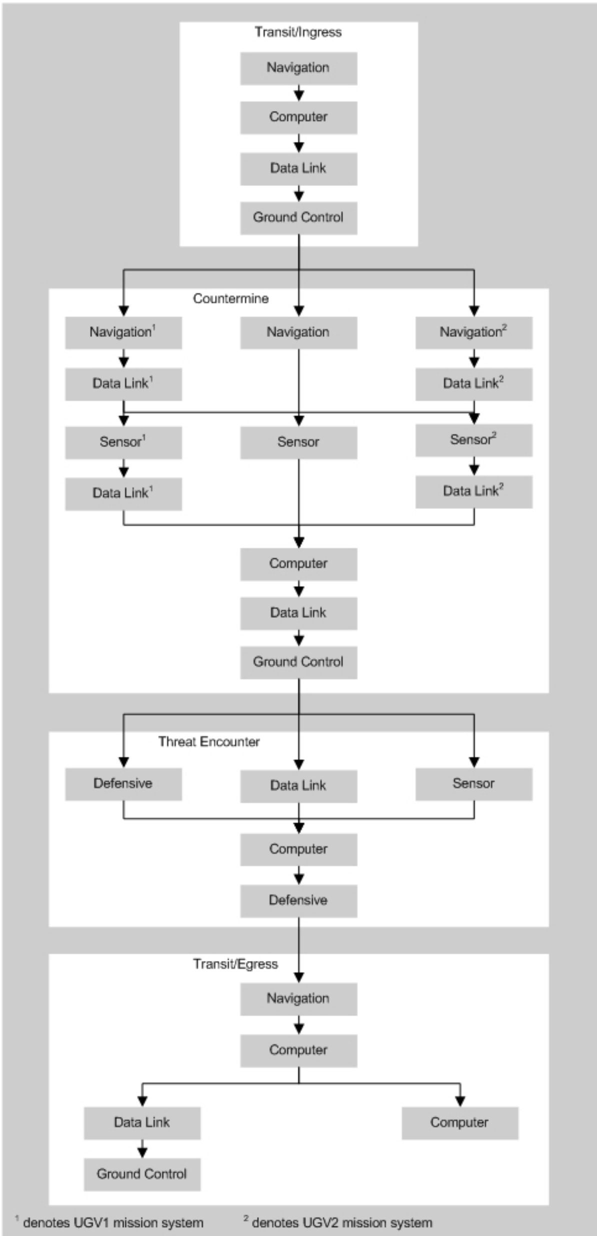


Figure 3: OC1 reliability block diagram

4.4 System Maintainability

Maintainability is a measure of the ability of a system, under state conditions of use, to be retained or restored to a state in which it can perform its required functions. It can be measured in terms of a combination of elapse times, personnel labour hour rates, maintenance frequencies, maintenance cost, and related logistic support factors. It can be measured by the repair rate of the system from the following [9, 10];

$$M(t) = e^{-\mu t} \tag{15}$$

where,
M(t) = maintainability function; μ = repair rate; and t = possible repair-time

Maintainability can be defined as the system 'mean time to repair' (MTTR);

$$MTTR = \frac{1}{\mu} \tag{16}$$

The maintainability analysis commences by identifying various combinations in which the subsystems, or mission systems as identified in the structural hierarchy [6], will require maintenance simultaneously, individually, or otherwise. The maintainability table is populated by identifying the probability of maintainability requirements; thus the creation of combinations in which the components may fail. The maintainability requirements of the combinations are then determined by assigning the maximum value.

The overall system maintainability of OC1 and OC2 is then evaluated as the mean maintainability of all the combinations using the following [9].

$$M_S = \frac{\sum_{i=1}^{n}\left(Mc_n \times Nc_n\right)}{\sum_{i=1}^{n} Nc_n} \tag{17}$$

where,
M_S = overall system maintainability; Mc_n = maintainability of combination; and
Nc_n = number of combinations.

Using the expressions above, the MTTR of the alternatives is then evaluated and used for comparison, to evaluate local vector of priorities for the AHP.

4.5 Functional Hierarchy

The functional hierarchy of the decision problem is illustrated in Figure 4. At the top level is the focus criterion 'Overall Mission Effectiveness' (OME), subsequent levels hosts the sub-criteria as identified in Section 4, while the last level consists of the alternatives as identified in Section 3.

4.6 Results

Results of the parametric analysis, described in Sections 4.1 to 4.4, are presented in Table 1.

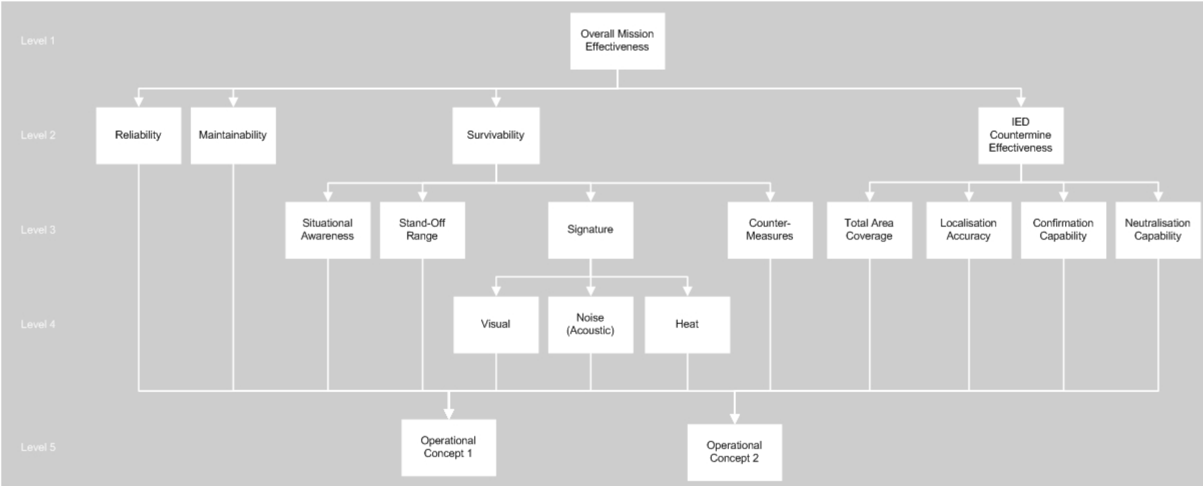


Figure 4: Functional hierarchy for countermine/IED detection operations

Table 1: Parametric results

Design Criteria	OC1	OC2
Reliability (MTBF)	249 Hours	205 Hours
Maintainability (MTTR)	48.85 Minutes	45.83 Minutes
Situational Awareness	High	Low
Stand-Off Range	Low	Low
Visual Signature	Medium	Medium
Noise Signature	Medium	Medium
Heat Signature	Medium	Medium
Countermeasures	High	High
Confirmation Capability	High	Low
Neutralisation Capability	High	No Capability

The plot for the total area coverage of OC1 and OC2 as a function of obstructed area, that can be used for pairwise comparison for AHP is presented in Figure 5.

The pairwise comparison of the localisation accuracy of OC1 and OC2 for AHP can be accomplished by analysing and comparing their respective distributions of case studies. As an illustration, Figure 6 illustrates the localisation accuracy of OC1 (Fused Probability of Airborne and Ground Sensor Probabilities) and OC2 (Airborne Sensor Probability) for a slightly inaccurate airborne measurement and moderately inaccurate ground measurements.

5. ESTABLISHING PRIORITIES

Based on the functional hierarchy (Figure 4), the AHP concept then compares the importance of design parameter weightings through its pairwise comparison technique using a 1-9 scale.

The relative weights, or local priorities, assigned to each decision criteria reflect the importance of the criteria to the 'Overall Mission Effectiveness'. The alternative solutions are then ranked similarly; where by, the results of the various parametric analyses are used to compare the alternatives against each other to designate their local priorities for the decision criteria in consideration. The local vectors of priorities are then synthesized to yield global vectors of priorities and an Overall Vector of Priority that ranks the alternatives, as illustrated in Figure 7.

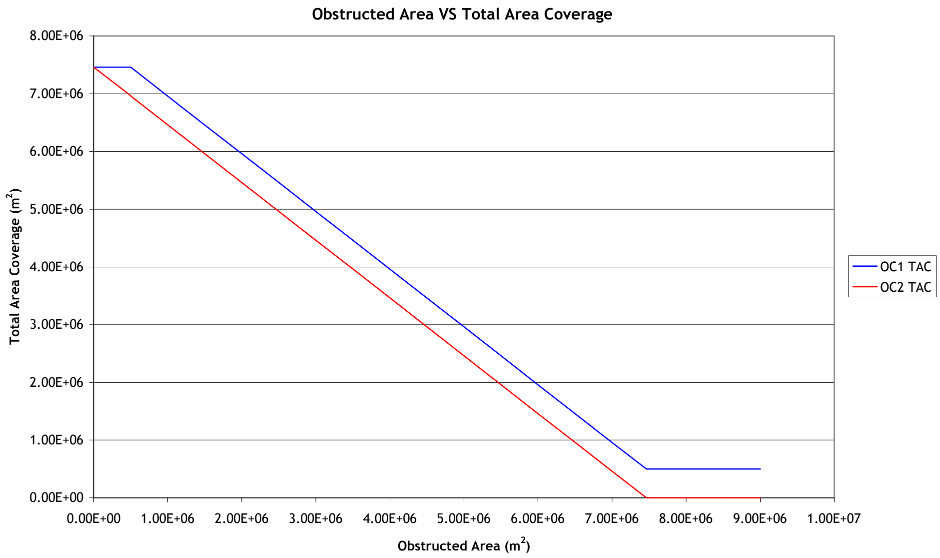


Figure 5: Total area coverage

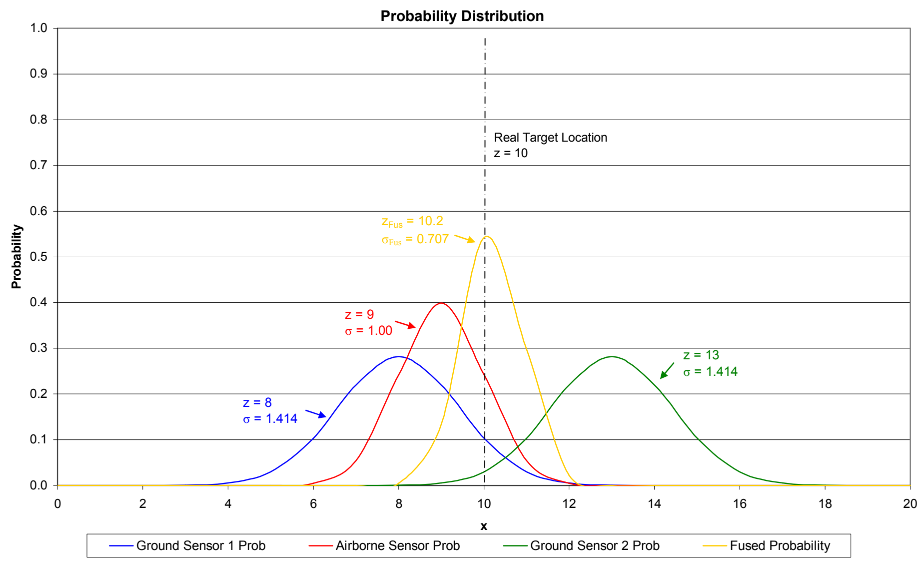
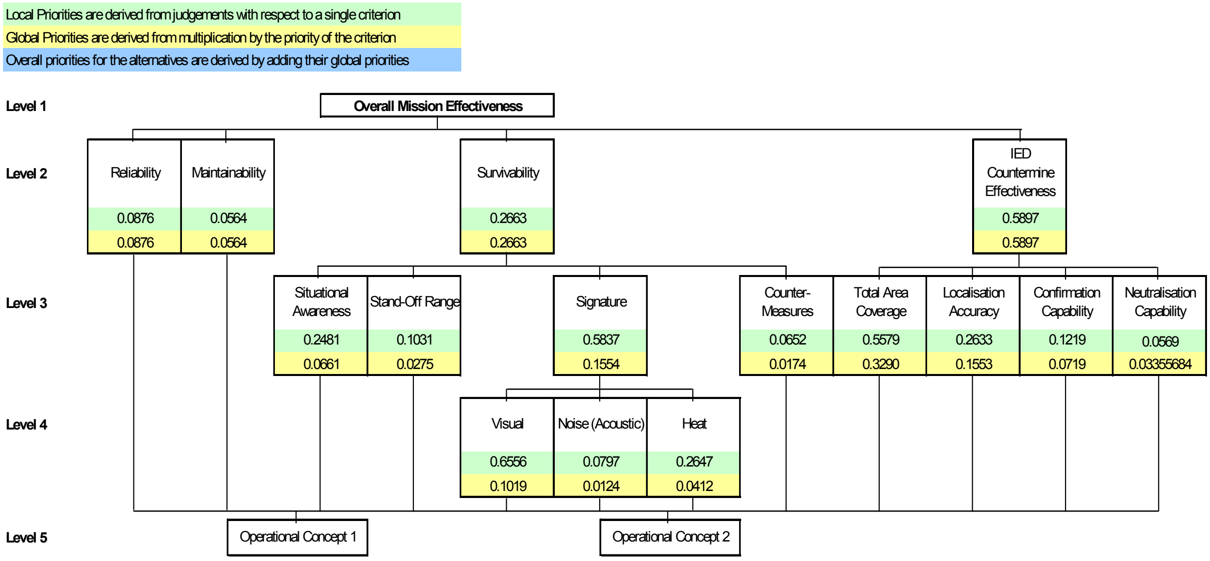


Figure 6: Localisation accuracy

6. DISCUSSION

The framework to evaluate the effectiveness was developed based on the AHP. The alternatives to be compared included the network centric system and a platform centric system. The decision criteria to evaluate the alternatives were identified as IED countermine effectiveness, survivability, reliability, and maintainability, with additional sub-criteria, and sub-sub-criteria, which was then placed in a functional hierarchy.

Through a pairwise comparison technique, the decision criteria were weighted against each other in terms of their parent criteria. The results of the parametric analysis of the alternatives were then used to compare the alternatives against each other to designate their local priorities for the decision criteria in consideration. This was then synthesised to rank the alternatives in terms of their overall mission effectiveness. This analysis found OC1 (network-centric system) is ranked higher than OC2 (platform-centric system) for IED countermine operations.



Criteria/Sub-Criteria/Sub-Sub-Criteria		Operational Concept 1		Operational Concept 2	
	Global Priority	Local Priority	Global Priority	Local Priority	Global Priority
Reliability	0.0876	0.7501	0.0657	0.2499	0.0219
Maintainability	0.0564	0.2499	0.0141	0.7501	0.0423
Situational Awareness	0.0661	0.8333	0.0551	0.1667	0.0110
Stand-Off Range	0.0275	0.5000	0.0137	0.5000	0.0137
Visual	0.1019	0.3333	0.0340	0.6667	0.0679
Noise (Acoustic)	0.0124	0.5000	0.0062	0.5000	0.0062
Heat	0.0412	0.5000	0.0206	0.5000	0.0206
Counter-Measures	0.0174	0.5000	0.0087	0.5000	0.0087
Total Area Coverage	0.3290	0.7501	0.2468	0.2499	0.0822
Localisation Accuracy	0.1553	0.8333	0.1294	0.1667	0.0259
Confirmation Capability	0.0719	0.8571	0.0616	0.1429	0.0103
Neutralisation Capability	0.0336	0.8889	0.0298	0.1111	0.0037
Overall Vector Priority			**0.6856**		**0.3144**

Figure 7: Overall vector priorities

7. CONCLUDING REMARKS

The AHP provides a suitable methodology to evaluate system designs. The framework captures all the facets required to evaluate a network centric system against an equivalent platform centric system in terms of mission effectiveness.

Having established the benefit of the interoperable design, the process is flexible to incorporate additional network centric alternatives for comparison; suitable in optimising the design for IED countermine operations (i.e. number and type of systems in the total system can be altered). Additionally, further research would assess the OME against an independent parameter, such as cost, to provide a more flexible design decision support tool.

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