EVALUATION OF AN INTEROPERABLE VERTICAL TAKE-OFF UAV FOR OPERATIONS WITH UGVS – AN OVERVIEW

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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). The Sir Lawrence Wackett Aerospace Centre has embarked on investigations and conceptual design studies of an interoperable VTUAV for IED detection operations with UGVs.

The conceptual design is evaluated based on the Analytical Hierarchy Process. The decision criteria by which the design is evaluated measures the total mission effectiveness of the system, in comparison to a platform centric system, for Counter-IED operations. Having evaluated the merits of interoperable design, additional network centric alternatives may be incorporated 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 future 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 from these perspectives [1-3].

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

2 Analytical Hierarchy Process

The AHP addresses multi-criteria decision making problems by explicit logical analysis to select the most optimum solution. It comprises of three concepts [5, 6]:

Structuring Hierarchies: A functional hierarchy is developed to establish the composition of the complex system according to its essential relationships. At the top level of the hierarchy, the problem and the objective of the system is identified. Subsequent levels with elements, governs the decision criteria, and further sub-criteria and sub-sub-criteria. The last level of the hierarchy comprises of the alternative solutions, linked to the decision criteria on which it is evaluated.

Setting Priorities: The priority of elements in the hierarchy in terms of its contribution is dictated by the objective of the system. Priority analysis involves pairwise comparisons of elements against a stipulated criterion in a matrix format. The qualitative assessments are transformed into quantitative values based on a scale of 1 to 9, where 1 is equal importance and 9 is extreme importance. The pairwise comparison matrix determines the local relative priorities, or "Vector-of-Priorities. The Vector-of-Priorities are synthesised for an Overall Vector-of-Priority to rank the alternatives. The highest rank denotes the optimum alternative.

Logical Consistency: The AHP measures the overall consistency of assessments by a 'Consistency Ratio' (CR). Inconsistencies in the matrices indicate the requirement of re-assessment.

3 Operational Concepts

To illustrate, the AHP evaluation compares two alternatives – a network-centric system and a platform-centric system for a Counter-IED operation as follows:

Operational Concept 1 (OC1): It is a network-centric system designed [7] by the interoperable design methodology [8-10]. The system consists of an iVTUAV capable of transporting two UGVs to the target area. The iVTUAV and UGV conduct joint Counter-IED operations. The iVTUAV provides wide area coverage while the UGVs provide precise detection, and target manipulation & inspection capabilities.

Operational Concept 2 (OC2): It is a platform-centric system designed by the traditional rotary wing design methodology [11]. The system consists of a VTUAV conducting a section of the Counter-IED operations independently, covering only the aerial component, with no precision detection and inspection capabilities.

The 'operational concept' of OC1 and OC2 are presented in Fig. 1 & Fig. 2 respectively.

4 Functional Hierarchy - Decision Criteria

The AHP evaluation compares two alternatives against various decision criteria. This evaluates the 'Total Mission Effectiveness' (TME) of the systems for the stipulated requirement of Counter-IED. To evaluate helicopter system effectiveness holistically [12], the design parameters that need to be considered are: (a) Mission capability; (b) Flight performance; (c) System reliability; (d) System maintainability; and (e) Cost.

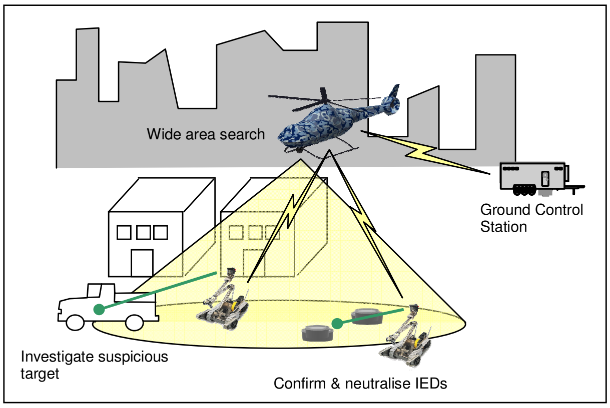

Fig. 1. Operational Concept 1

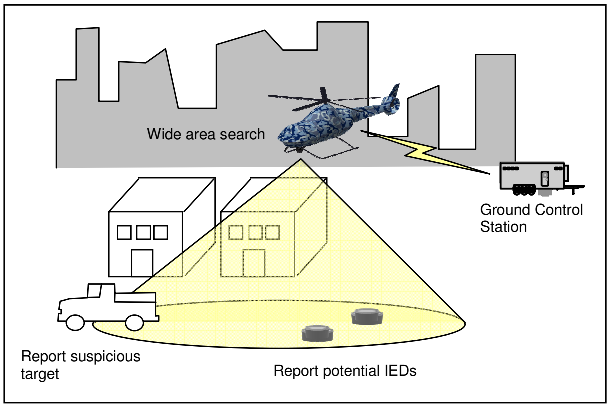

Fig. 2. Operational Concept 2

The slated parameters are for a traditional platform-centric helicopter system [12]. Additional parameters need to be considered for the system-of-systems concept of NCW – OC1. The parameters include 'Counter-IED effectiveness' and 'Survivability' for further identification of sub-parameters. 'Mission capability' is reflected as Counter-IED effectiveness, being the focus. Survivability is now considered separately to address the specific requirements for Counter-IED in a hostile environment. 'Flight performance', being a base system performance parameter, is not included when comparing system-of-systems performances. Cost, not being an applicable measure of Total Mission

Effectiveness, is subsequently considered for 'Cost Effectiveness' (CE). A comparative analysis of CE with the mission effectiveness will provide the avenue to evaluate the 'Total System Effectiveness' (TSE).

The functional hierarchy of the decision process is presented in Fig. 3. At the top level (Level I) is 'Total Mission Effectiveness' (TME) of the systems. Subsequent levels (Levels II, III, & IV) cover the decision criteria and sub-criteria. The last level (Level V) presents the alternative operational concept solutions, which are used for comparative analysis to evaluate TME, based on the criteria and sub-criteria.

5 Total Mission Effectiveness – Parametric Analysis

The parameters to evaluate the TME are the decision criteria presented in its functional hierarchy (Fig. 3). These are to be quantitatively evaluated for comparative analysis of the alternative operational concepts to support operational and design decisions.

5.1 Counter-IED Effectiveness

The decision sub-criteria identified for evaluating Counter-IED effectiveness are as follows: (a) Mission area coverage; (b) Localisation accuracy; (c) Confirmation capability; and (d) Neutralisation capability.

Mission Area Coverage:
The mission area coverage is the degree to which the area-of-interest a system is capable to survey. This is governed by the velocity of the system, time, and sensor swath of the system. Mathematically, it is evaluated [13] as follows:

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

where,
A = area coverage; V = velocity of system;
t = search time; and W = sensor swath.

The velocity of the airborne platforms is mission requirements and design governed, while the velocity of the ground off-the-shelf platforms is obtained from the proprietary data. Search time for both platforms is in accordance to the mission. As the proprietary data on sensor swath is not in public domain, it is mathematically estimated [14] as follows for illustration:

$$W = 0.68 \times D \qquad (2)$$

where,
W = sensor swath; and D = distance

Distance for the airborne platform (VTUAV) is its operational design altitude. The ground platform's sensor range is considered as 50 metres for illustration.

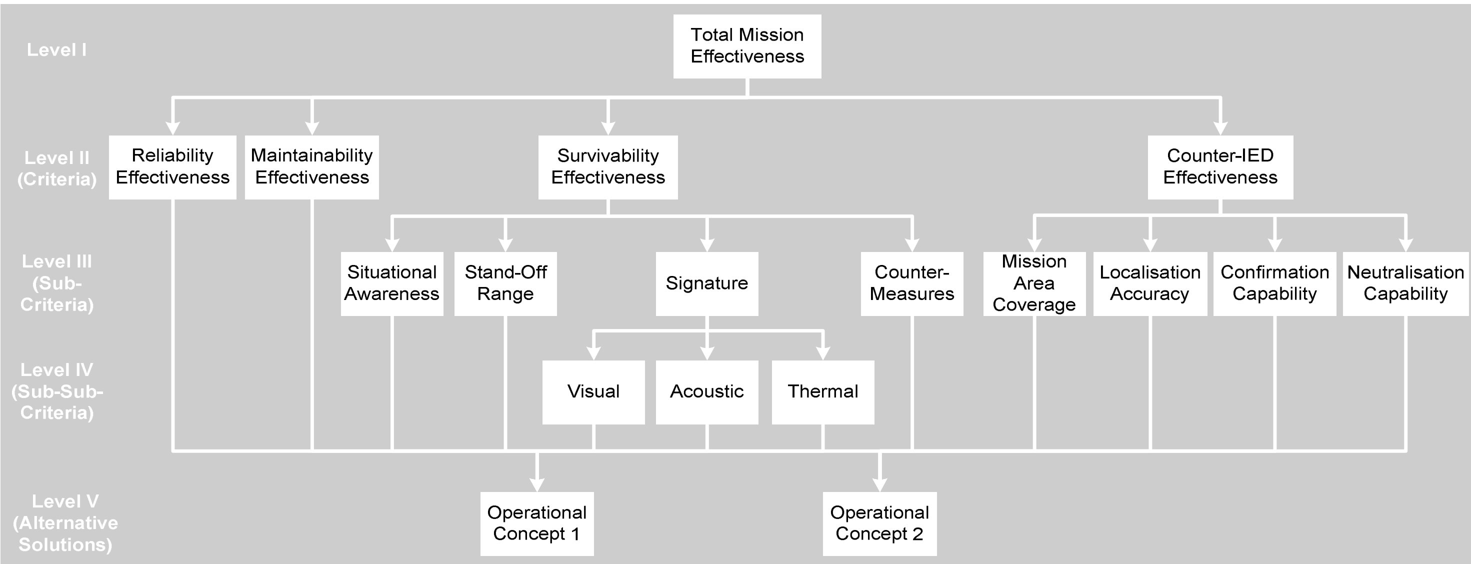

Fig. 3. Functional Hierarchy of Decision Parameter – Total Mission Effectiveness

Being an urban environment, the search area of the airborne platform is limited by buildings, vehicles, and other obstructions. The area coverage of a ground platform is assumed unaffected due to its ground manoeuvrability.

A system-of-systems (network-centric) total area coverage is the aggregate of all area covered by all platforms, with no re-coverage of areas. Thus, for OC1, the total area covered by iVTUAV and UGV is evaluated from the following:

$$TAC = A_{UAV} \quad \text{when } A_O \le A_{UGV} < A_{UAV} \tag{3}$$

$$TAC = A_{UAV} - A_O + A_{UGV} \quad \text{when } A_{UGV} < A_O < A_{UAV} \tag{4}$$

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

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 as follows:

$$TAC = A_{UAV} - A_O \quad \text{when } A_O < A_{UAV} \tag{6}$$

$$TAC = 0 \quad \text{when } A_{UAV} \le A_O \tag{7}$$

The total area coverage of OC1 and OC2 are plotted as a function of total obstructed area (Fig. 4) for comparative analysis to evaluate local vector of priorities for the AHP.

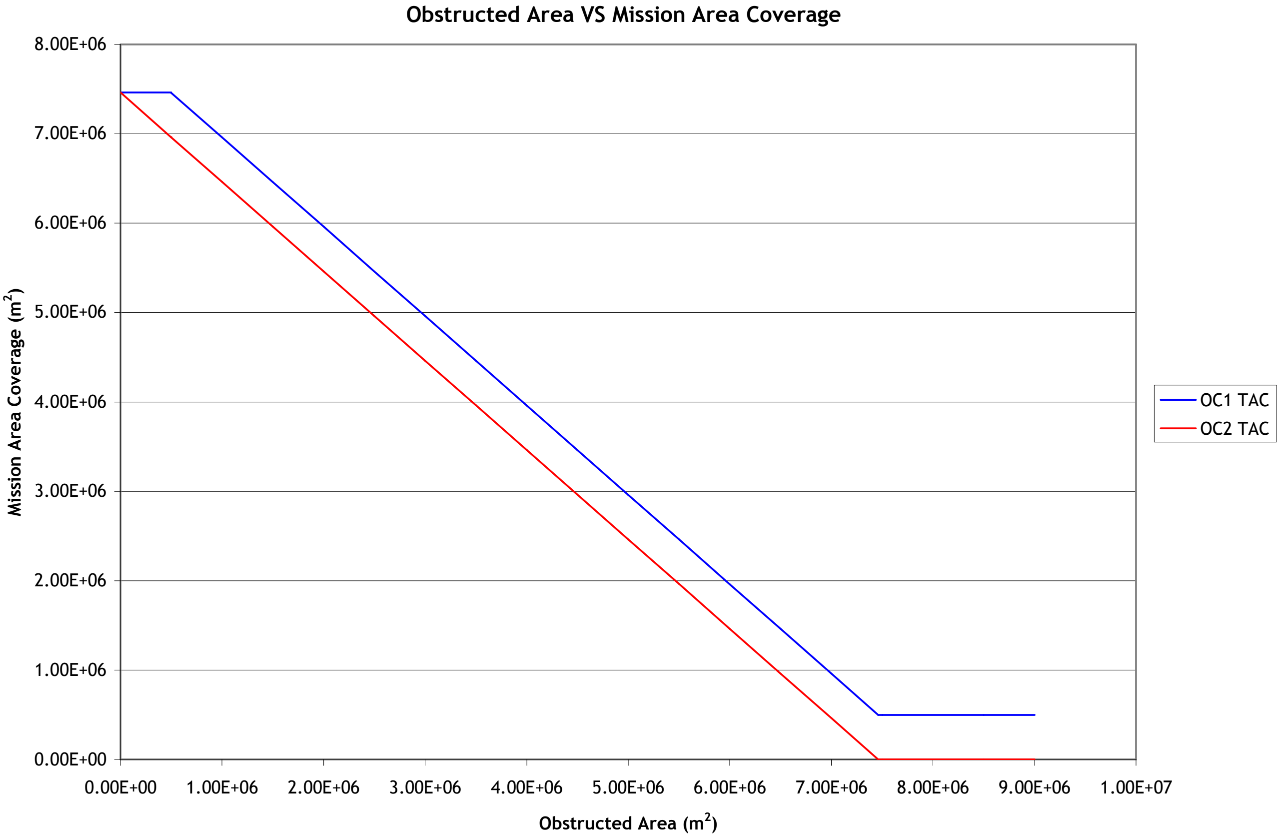

Fig. 4. Mission Area Coverage

Localisation Accuracy:
Localisation accuracy measures the degree-of-accuracy of a sensor in determining target location, in a cluttered environment. Gaussian distribution provides a probabilistic representation of sensor uncertainty [15]. Multi-sensor data fusion enhances the degree-of-accuracy, and fusion of multi-sensor based measurements is achieved by adopting occupancy grid Bayesian framework based on Independent Opinion Pool [15].

The Independent Opinion method does not provide any decision support on disparate measurements [15]. Thus, taking into account all sensors' certainty and reliability in a Bayesian framework, the Gaussian distribution of data fusion measurements is expressed as follows [15]:

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

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,

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

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

A case study is considered for the purpose of comparative analysis. OC1 is considered as the Fused Probability of Airborne and Ground Sensor Probabilities, and OC2 is considered as only the Airborne Sensor Probability. Since real models of sensor uncertainties are commercial-in-confidence, to illustrate, it is assumed that the airborne sensor (for both OC1 and OC2) has a certain degree-of-uncertainty (i.e. $\sigma^2 = 2$) while the ground sensors (for OC1) are with higher grades of uncertainties (i.e. $\sigma^2 = 3$). Using the expression above (Eqn 9), the fused sensor uncertainty is evaluated as $\sigma^2 = 0.8571$.

The location point (x) for the real target location is considered as x = 0m. Using Microsoft Excel®, a sample size of 100 localisation measurements for each sensor is randomly generated based on each sensor's probability distributions where the sensor's expected target location, 'z' = 0. The real target location is assumed unknown for each sample measurement, and thus, the generated location points (x) are the sensor's expected target location (z) and the distributions plotted accordingly. The fused expected locations are evaluated and distributions plotted similarly using the Bayesian Theorem expressions (Eqns 8 - 10) for each sample measurement. As an illustration, one distribution of the sample is presented in Fig. 5.

The 'Root Mean Square Errors' (RMSE) of OC1 and OC2 total sample of measurements of expected target location (z) to the real target location (x = 0m) is evaluated as 1.4955m and 2.0011m respectively. The distribution plots and RMSE of OC1 and OC2 are compared to evaluate local vector of priorities for the AHP.

Confirmation Capability:
Suspected objects detected by sensors need to be confirmed as IEDs. A cluttered environment leads to false alarms which hinders the effectiveness of an operation [16]. The performance of present technologies are limited and not very effective in all settings [17], hence are field tested to establish performances in detecting and confirming targets [16].

As the alternative designs are still in their preliminary phases, premature measurement of the confirmation capability is estimated based on an assessment matrix where confirmation is dependent on the following: (a) False alarm rate of the sensor; (b) Systems inspection distance; and (c) Capability to probe/manipulate the area/object of interest. The total system in consideration is allocated scores based on these parameters. The total score is a measure of the confirmation capability.

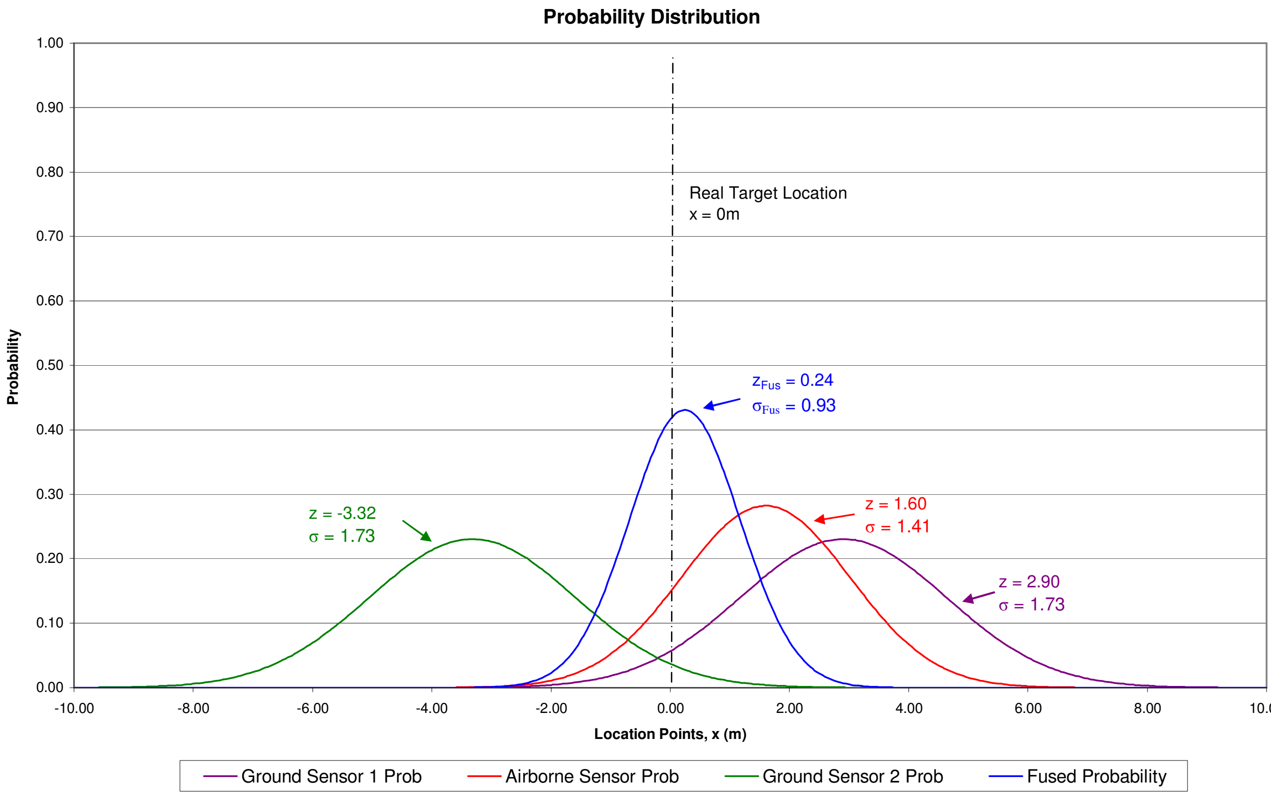

Fig. 5. Localisation Accuracy

Real values of sensor false-alarm rates are proprietary data. Thus, in the payload design, it is assumed equal for both OC1 and OC2. The confirmation capability scores of OC1 and OC2 were evaluated as 14 ('High') and 6 ('Low') respectively, and are compared to evaluate local vector of priorities for the AHP.

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 [9]. Based on the number of defensive systems and miscellaneous systems in the payload design that contribute to EOD, the neutralisation capabilities of OC1 and OC2 were estimated as 'High' and 'No Capability' respectively, and are compared to evaluate local vector of priorities for AHP.

5.2 Survivability

The decision sub-criteria identified for evaluating survivability effectiveness are as follows: (a) Situational awareness; (b) Stand-off range; (c) Signature reduction; and (d) Countermeasures.

Situational Awareness:
Information sharing and situational awareness amongst systems in a network enables collaboration and self-synchronisation, to enhance survivability [4, 18]. The degree of situational awareness is estimated by an assessment matrix which includes the following: (a) Systems integrated in the network; (b) Degree-of-communication across systems; and (c) Criticality 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 a system. The degree-of-

situational awareness scores of OC1 and OC2 were evaluated as 14 ('High') and 6 ('Low') respectively, and are compared to evaluate local vector of priorities for the AHP.

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 [19]. In this case study, since OC1 and OC2 will operate in the same threat environment, the stand-off range is simply measured as the operating altitude of the VTUAVs, where a higher altitude provides greater survivability.

UAV operating altitudes are classified [19] as low (below 10,000 ft), medium (10,000-30,000 ft), and high (above 25,000 ft). Since threat from shoulder launched IR missiles is capable of reaching medium altitudes [19], comparison of altitudes is more significant based on altitude classification, rather than marginal differences within each classification. The operating altitudes of OC1 and OC2 are considered as both 'Low', based on the design requirements, and are compared to evaluate local vector of priorities for the AHP.

Signature:
Signature reduction enhances survivability by limiting the capability of the adversary to detect the system and follow offensive action [11]. The type of signatures and the mode adopted to address survivability is as follows:

- **Visual:** This signature is governed by physical size of the system (VTUAV), where survivability is enhanced by smaller designs. UAVs are classified [19, 20] as micro, small, medium, and large based on its maximum take-off weight, wingspan, operating altitude, and speed. The size difference is significant between the variant classifications, but does vary within the classifications. The sizes and thus visual signature of the VTUAVs in OC1 and OC2 are considered as both 'Medium', based on the design parameters, and are compared to evaluate local vector of priorities for the AHP.

- **Acoustic:** The main contributors to noise [11, 19, 21] are the powerplant, and rotors. The acoustic signature is estimated based on an assessment matrix which includes the following: (a) Type of powerplant – electric, turbine, diesel, solar-powered and futuristic technologies; (b) Location – external or internal; (c) Tip shape and speed – lower tip speeds and non-squared tip shapes provides low acoustic signatures; and (d) Tail rotor configuration – NOTAR anti-torque system reduces acoustic signature. The system in consideration is allocated scores based on these parameters. The total score is a measure of the acoustic signature. The acoustic signature scores of the VTUAVs in OC1 and OC2 were evaluated as both 20 ('Medium'), and compared to evaluate local vector of priorities for the AHP.

- **Thermal:** The major source of heat [22, 23] is the propulsion subsystem of the VTUAV. The thermal signature is estimated based on an assessment matrix which includes the following: (a) Mufflers that reduce heat from engine exhaust; (b) Heat-absorbing materials; and (c) Cold air mixing that reduces heat from the engine exhaust. Air friction creates heat on the leading edges of an aircraft. As significant thermal signature occurs only at very high speeds [23], it is neglected for this case study. The system in consideration is allocated scores based on these parameters. The total score is a measure of the thermal signature. The thermal signature scores of the VTUAVs in OC1 and OC2 were evaluated as both 14 ('Medium'), and are compared to evaluate local vector of priorities for the AHP.

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 [11, 24]. 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. As the key threat includes adversary IR missiles, the

survivability contribution from the countermeasures of the VTUAVs in OC1 and OC2 is estimated as both ‘High’. The estimates are compared to evaluate local vector of priorities for the AHP.

5.3 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. It can be measured [12, 13] by the failure rate of the system from the following:;

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

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);

$$MTBF = \frac{1}{\lambda} \qquad (12)$$

The reliability of the total system is governed by the individual subsystem reliabilities in its operational set-up that comprises of the following: (a) Series in which all components in the system operate for the operational effectiveness of the whole system; (b) Parallel if only one component needs to operate for the operational effectiveness of the whole/partial system; and (c) Combined in which the components are in series and in parallel. The operational set-up is represented by developing a reliability block diagram comprising of the systems in series/parallel. The system is operationally effective by an uninterrupted path between input and output of the system. The mathematical expressions to evaluate reliability of systems in series and parallel are as follows [12, 13]:

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

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

where,
$R_{S(Series)}$ = total system reliability of systems operating in series;
$R_{S(Parallel)}$ = total system reliability of systems operating in parallel; and
R_i = component reliability.

The subsystems/mission systems presented in the structural hierarchy [9] were categorised into six components – Navigation, Sensors, Computer, Defensive Systems, Weapons, and Data Link. The total system reliability of OC1 and OC2 is evaluated by integrating the six mission system components in an operational sequence, to develop the reliability block diagram. The VTUAV mission systems reliability values for illustration are assumed to be of similar helicopter mission systems, which were evaluated [12] from manufacturer data. The expressions above (Eqns 13 - 14) are applied to evaluate the MTBF.

As an illustration, the reliability block diagram of OC1 is presented in Fig. 6. The MTBF of OC1 and OC2 were evaluated as 249 Hours and 205 Hours respectively, using Microsoft Excel®, and are compared to evaluate local vector of priorities for the AHP.

While OC1 provides higher complexity, suggesting more failures, its MTBF is found higher than OC2 due to a greater number of redundant subsystems operating in parallel, thus providing higher probability that the total system will continue to perform in a satisfactory manner for a given period of time.

5.4 System Maintainability

Maintainability is a measure of the ability of a system to be retained or restored to a state in which it can perform its required functions. It is measured in terms of a combination of elapse times, personnel labour hour rates, maintenance frequencies, maintenance cost, and related logistic support factors. It is measured by the repair rate of the system as follows [12, 13]:

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

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

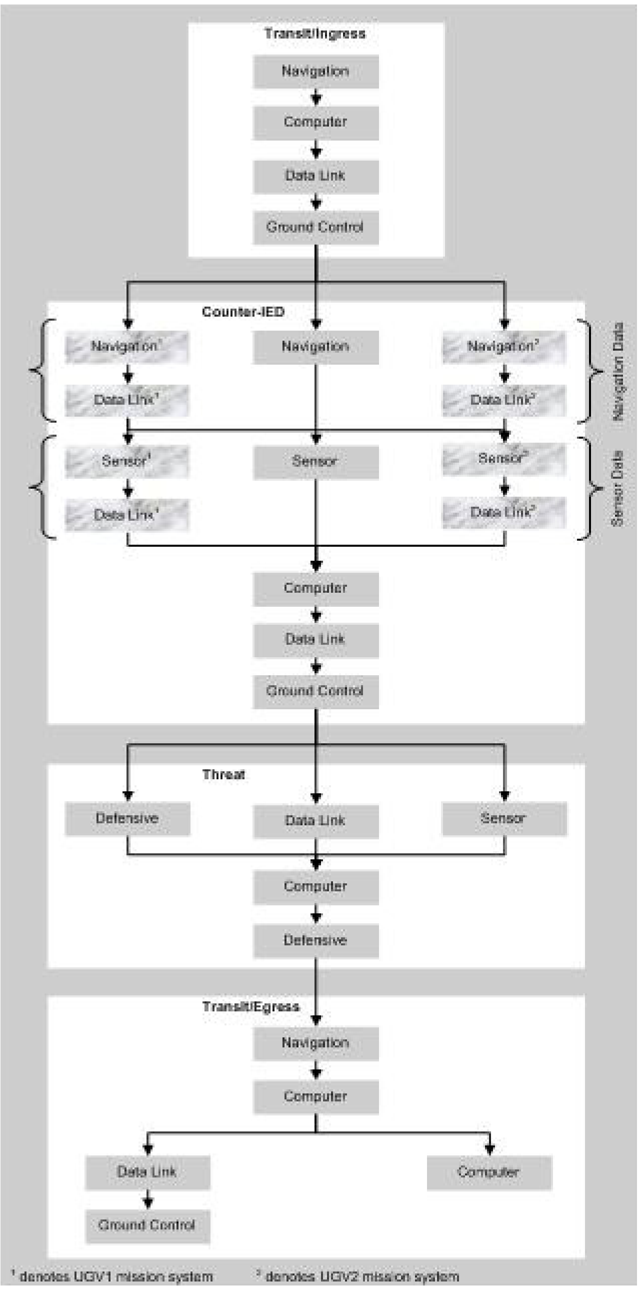

Fig. 6. OC1 reliability block diagram

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

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

The maintainability analysis involves the identification of subsystem/mission system [9] combinations for maintenance. The maintainability of the combination is determined based on the maximum maintainability of the component in the combination. The VTUAV mission systems maintainability values for illustration are assumed to be of similar helicopter mission systems, which were evaluated [12] from manufacturer data.

The total maintainability (MTTR) of OC1 and OC2 is evaluated as the mean MTTR of all the combinations as follows [12]:

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

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

The maintainability table of failure combinations is populated using Matlab® and imported into Microsoft Excel® to evaluate MTTR. The MTTR of OC1 and OC2 were evaluated as 48.85 Minutes and 45.83 Minutes respectively, and are compared to evaluate local vector of priorities for the AHP.

6 Prioritisation Assessment

The results of the various parametric analyses inter-compare the alternatives to designate its local priorities for the decision criterion in consideration. The local vectors of priorities are then synthesised to yield global vectors of priorities and an Overall Vector of Priority that ranks the alternatives. The Overall Vector of Priority of OC1 and OC2 were evaluated as 0.6727 and 0.3273 respectively, ranking OC1 higher than OC2.

7 Cost Effectiveness

The cost parameter is now considered to evaluate the CE of the two operational concepts, OC1 and OC2. The TME and the CE are subsequently compared to provide a pragmatic decision support tool for decision trade-offs.

The 'Life Cycle Cost' (LCC) is the total cost of a system through its entire life cycle and covers concept design (1%), development (7%), demonstration (1%), production (15%), operations (75%), and disposal (1%) [25].

The total system cost of OC1 consists of the LCC of the iVTUAV, UGVs, and Ground Equipment. The total system cost of OC2 consists of the LCC of the VTUAV, and Ground Equipment.

The VTUAV production costs are estimated as the average of two methodologies.

- **Methodology 1:** It utilises the VTUAV empty weight [19] in cost evaluation as follows:

$$UAV.Cost_{Pro}(FY02.US\$) = 1500 \times W_E \qquad (18)$$

where,
UAV $Cost_{Pro}$ = UAV production cost; and
W_E = empty weight in pounds.

- **Methodology 2:** It utilises the VTUAV gross weight [26] in cost evaluation as follows:

$$UAV.Cost_{Pro}(FY03.US\$) = 12550 \times W_g^{0.749} \times e^{-0.371} \qquad (19)$$

where,
UAV $Cost_{Pro}$ = UAV production cost; and
W_g = gross weight in pounds.

The Ground Equipment production costs are estimated [26] from the following:

$$GE.Cost_{Pro}(FY03.US\$) = 433400 \times R^{0.507} \times e^{0.398} \qquad (20)$$

where,
GE $Cost_{Pro}$ = ground equipment production cost; and
R = range of UAV from ground equipment in nautical miles.

The production cost (unit price) of the PackBot UGV is FY02.US$45,000 [27]. The LCC breakdown of all systems and total system LCC of OC1 and OC2 is presented in Table 1, where the concept design, development, demonstration, operations, and disposal costs are evaluated based on a percentage of production cost, as identified above [25]. Since the UGVs are commercial off-the-shelf systems, and since the Ground Equipment is assumed to utilise commercial off-the-shelf subsystems, the concept design, development, and demonstration costs are not considered. The total system LCC of OC1 and OC2 were evaluated as FY07 US$ 41.73 million and FY07 US$ 37.16 million respectively.

8 Total System Effectiveness

The TME and normalised LCC of OC1 and OC2 are plotted (Fig. 7) to analyse the TSE of the two operational concepts. The TSE is the ratio of TME to normalised LCC. The TSE of OC1 and OC2 were evaluated as 1.2717 and 0.6949 respectively. This indicates significant gain in TME for a marginal gain in cost, for OC1; as compared to OC2.

9 Results and Discussion

Functional Hierarchy & Operational Concepts: The functional hierarchy format provided the avenue to effectively analyse operational and design parameters for prioritisation assessment of the operational concepts.

Parametric Analysis & Prioritisation Assessment: The results of the parametric analyses quantitatively evaluated the operational concepts effectiveness for comparative analysis. The concepts were weighted against each other to designate the local priorities in regards to the decision criterion in consideration. The vector of priorities were synthesised to rank the concepts in terms of TME. This analysis resulted in OC1 (network-centric system) being ranked at 0.6727, higher than OC2 (platform-centric system) at 0.3273 for Counter-IED operations.

Table 1. Total System Life Cycle Cost

	Life Cycle							
	Acquisition Phase				Utilisation Phase			
	Concept Design Cost (1%)	Development Cost (7%)	Demonstration Cost (1%)	Production Cost (15%)	Operation Cost (75%)	Disposal Cost (1%)	Sub-Total	**Total System Life Cycle Cost**
OC1 iVTUAV	122	855	122	1,832	9,160	122	12,213	**41,729**
OC1 UGV1[¥]	N/A	N/A	N/A	51	257	3	311	
OC1 UGV2[¥]	N/A	N/A	N/A	51	257	3	311	
Ground Equipment^	N/A	N/A	N/A	4,763	23,813	318	28,894	
Sub-Total	122	855	122	6,697	33,487	446		
OC2 VTUAV	83	579	83	1,240	6,199	83	8,267	**37,161**
Ground Equipment^	N/A	N/A	N/A	4,763	23,813	318	28,894	
Sub-Total	83	579	83	6,003	30,012	401		

(All values in FY07 US$K)

[¥] FY07 price calculated using a US Consumer Price Index (CPI) / Inflation Rate of 14.29% from Jan 2002 - Jan 2007 (CPI found from www.InflationData.com)

^ FY07 price calculated using a US Consumer Price Index (CPI) / Inflation Rate of 11.40% from Jan 2003 - Jan 2007 (CPI found from www.InflationData.com)

^ Based on range of 41.663 nautical miles (51.44 m/s cruise speed for transit time of 25 minutes = 77.16 km)

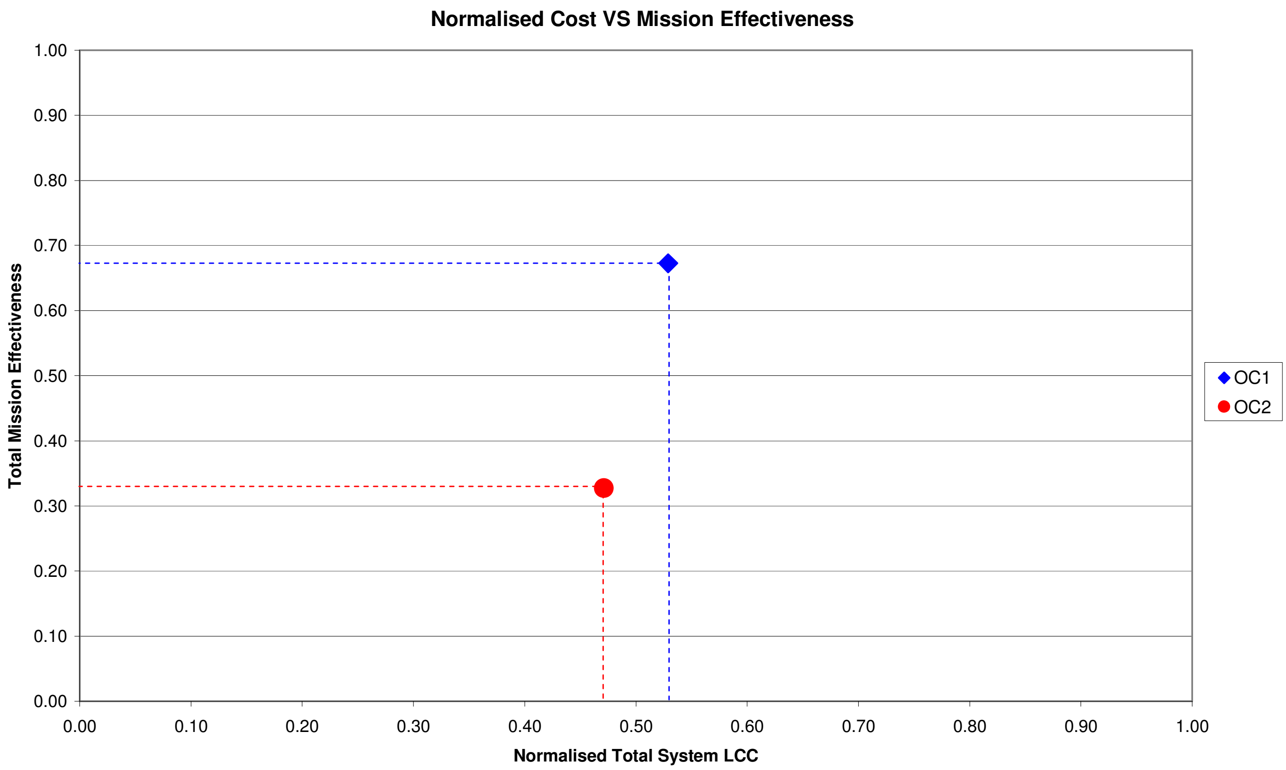

Fig. 7. Total System Effectiveness

The case study (OC1 and OC2) illustrates the merits of operating a network-centric system over a platform-centric system from a mission effectiveness perspective.

Cost Effectiveness:
Costs for OC1 and OC2 were evaluated based on the estimated LCC of the total system for illustration. The evaluation resulted in the OC1

concept with a higher life cycle cost of FY07 US$ 41.73 million compared to OC2 at FY07 US$ 37.16 million.

Total System Effectiveness:
The TSE plot illustrates significant gain in TME for a marginal gain in cost for OC1; as compared to OC2. Thus, the total system effectiveness of OC1 outpaces that of OC2.

The TSE is thus a pragmatic design decision support tool. It illustrates the enhancements in the degree-of-mission effectiveness for each unit increase in cost.

10 Concluding Remarks

The AHP provides an avenue for developing methodologies to evaluate system operational and design parameters in quantitative terms. The methodology developed captures all the disparate parameters required to evaluate the total system effectiveness of network-centric designed system against a platform-centric designed system from an operational and cost perspective.

The interoperable design (network-centric) provided a significant degree of total system effectiveness (mission and cost effective solution) over the platform-centric design in Counter-IED operations. The comparative process, using AHP, is flexible to incorporate additional network-centric operational concepts for comparative analysis. This provides optimisation of the total system design for interoperability by stipulating the optimum integration of number and type of systems in the total system.

References

[1] Anon. *Field manual 20-32: Mine/Countermine operations*, Report from the Department of the Army, Washington, USA, 2005.

[2] Anon. *Joint robotics program: Master plan 2005*, Report from the Defense Systems/Land Warfare and Munitions, Washington, USA, 2005.

[3] Eshel, D. Future roles for UAVs, *Asia-Pacific Defence Reporter*, vol. 31, no. 6, pp.38-40, 2005.

[4] Anon. *The implementation of network-centric warfare*, Report from the Office of Force Transformation, Secretary of Defense, Washington, USA, 2005.

[5] Saaty, T.L. *Decision making for leaders: The analytic hierarchy process for decisions in a complex world*, RWS Publications, USA, 2001.

[6] Jaiswal, N.K. *Military operations research: Quantitative decision making*, Kluwer Academic Publishers, Boston, USA, 1997.

[7] Khreish, J., Sinha, A. & Winata, L. Conceptual design of an interoperable vertical take-off unmanned aerial vehicle for operations with unmanned ground vehicles, *Proceedings of the 22nd International UAV Systems Conference,* Bristol, UK, 2007.

[8] Khreish, J. & Sinha, A. Design of a vertical take-off unmanned aerial vehicle with interoperable capabilities - mission analysis phase, *Proceedings of the 62nd Annual AHS Forum,* Phoenix, Arizona, 2006.

[9] Khreish, J. & Sinha, A. Design approach for a vertical take-off unmanned aerial vehicle with interoperable capabilities - payload issues, *Proceedings of the 25th International Congress of the Aeronautical Sciences,* Hamburg, Germany, 2006.

[10] Khreish, J. & Sinha, A. Conceptual design of an interoperable vertical take-off unmanned aerial vehicle for operations with unmanned ground vehicles, *Proceedings of the 22nd International UAV Systems Conference,* Bristol, UK, 2007.

[11] Sinha, K.A. *Introduction to preliminary helicopter design*, Department of Aerospace Engineering, RMIT, Melbourne, Australia, 2002.

[12] Kusumo, R. An integrated decision support system for mid-life upgrade of maritime helicopters, PhD thesis, RMIT University, Melbourne, Australia, 2002.

[13] Przemieniecki, J.S. *Mathematical methods in defense analyses*, 3rd edn, American Institute of Aeronautics and Astronautics, Viginia, USA, 2000.

[14] Steinvall, O., et al. *Laser based 3-D imaging: New capabilities for optical sensing*, Report from the Swedish Defence Research Agency, Linkoping, Sweden, 2003.

[15] Kumar, M., Garg, D.P. & Zachery, R. Multi-sensor fusion strategy to obtain 3-D occupancy profile, *Proceedings of the 31st Annual Conference of IEEE Industrial Electronics,* Raleigh, NC, pp.2083-2088, 2005.

[16] Altshuler, T.W., Andrews, A.M. & Sparrow, D.A. Mine and UXO detection: Measures of performance and their implication in real-world scenarios, *Proceedings of the SPIE Detection and Remediation Technologies for Mines and Minelike Targets II,* Orlando, USA, pp.281-292, 1997.

[17] MacDonald, J., et al. *Alternatives for landmine detection*, Report from the RAND Institution, USA, 2003.

[18] Meyer, P.K. Realizing UAV's transformational potential: The emerging technology agenda,

Proceedings of the AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio, 2003.

[19] Anon. *Unmanned aircraft systems roadmap: 2005 - 2030*, Report from the Office of the Secretary of Defense, Washington, USA, 2005.

[20] Bil, C., et al. *Introduction to unmanned aerial vehicle technology*, Department of Aerospace Engineering, RMIT, Melbourne, Australia, 2002.

[21] Anon. 2007, *NOTAR*, Wikipedia, viewed 28 June 2007, <http://en.wikipedia.org/wiki/NOTAR>.

[22] Day, D.A. (n.d.), *Stealth aircraft*, U.S. Centennial of Flight Commission, viewed 28 June 2007, <http://www.centennialofflight.gov/essay/Evolution_of_Technology/Stealth_aircraft/Tech31.htm>.

[23] Anon. 2003, *Designing for stealth*, Nova: Science Programming on Air and Online, viewed 28 June 2007, <http://www.pbs.org/wgbh/nova/xplanes/stea-nf.html>.

[24] Jackson, D. 2004, *Missile countermeasures*, Aerospaceweb.org, viewed 28 June 2007, <http://www.aerospaceweb.org/question/electronics/q0191.shtml>.

[25] Clark, G., Piperias, P. & Traill, R. Life-cycle cost/capability analysis for defence systems, *Proceedings of the Simulation Technology and Training Conference,* Melbourne, Australia, 1999.

[26] Anon. Unmanned aerial vehicle system acquisition cost estimating methodology, *Proceedings of the 37th DoD Cost Analysis Symposium, 11-13 February*, 2004.

[27] Robertson, N. 2002, *Meet Packbot: The newest recruit*, CNN.com/SCI-TECH, viewed 9 August 2006, <http://archives.cnn.com/2002/TECH/science/08/01/packbot/>.

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