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14. ABSTRACT
This paper describes a defensible process for selecting the combinations of feasible and viable technologies that have the highest potential to mitigate the current U.S. Army Training and Doctrine Command (TRADOC) capability gaps for helicopters operating in a Degraded Visual Environment (DVE). The process for selecting these combinations is an adaptation of traditional Systems Engineering techniques, including Morphological Analysis, Quality Function Deployment, and Utility Theory. After they are identified, the Army intends to examine the inclusion of the top combinations (or a subset thereof) into ground, simulation, and flight test activities in order to better understand their ability to mitigate the gaps.

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A Systems Engineering Process for Selecting Technologies to Mitigate the Risk of Operating Rotorcraft in Degraded Visual Environments

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Abstract

This paper describes a *defensible* process for selecting the combinations of *feasible* and *viable* technologies that have the highest potential to mitigate the current U.S. Army Training and Doctrine Command (TRADOC) capability gaps for helicopters operating in a Degraded Visual Environment (DVE). The process for selecting these combinations is an adaptation of traditional Systems

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Engineering techniques, including Morphological Analysis, Quality Function Deployment, and Utility Theory. After they are identified, the Army intends to examine the inclusion of the top combinations (or a subset thereof) into ground, simulation, and flight test activities in order to better understand their ability to mitigate the gaps. Additionally, if technologies present a unique capability of interest, the specific technology may be examined further.

Nomenclature

AAD	Aviation Development Directorate
AATD	Aviation Applied Technology Directorate
AMRDEC	Aviation & Missile Research Development & Engineering Center
ADS	Aeronautical Design Standard
AFDD	Aeroflightdynamics Directorate
AHP	Analytic Hierarchy Process
BAE	British Aerospace Engineering
CERDEC	U.S. Army Communications-Electronics Research, Development and Engineering Center
DSE	Decision Support Environment
DVE	Degraded Visual Environment
EO/IR	Electro-Optic/Infra-Red
FNA	Functional Needs Analysis
GTRI	Georgia Tech Research Institute
LADAR	Laser Radar (analogous to LIDAR)
LIDAR	Light Detection and Ranging (analogous to LADAR)

MADM	Multi-Attribute Decision Making
MMWR	Millimeter-Wave Radar
MTE	Mission-Task Element
NOE	Nap of the Earth
NVESD	Night Vision & Electronics Sensors Directorate
OPSEC	Operational Security
PEO	Program Executive Office
QFD	Quality Function Deployment (a.k.a. House of Quality)
SME	Subject Matter Expert
SNC	Sierra Nevada Corporation
SSDD	System Simulation & Development Directorate
TRADOC	U.S. Army Training and Doctrine Command
UCE	Usable Cue Environment
UH	Utility Helicopter

Introduction

In July 2012, the U.S. Army began the AMRDEC DVE Mitigation Program in order to execute a synchronized, collaborative effort across the AMRDEC Science & Technology community to parametrically define flight control system, cueing, and sensor combinations which enable the "closing" of the current TRADOC capability gaps that pertain to rotorcraft operations in degraded visual environments. Additionally, through analysis, simulation, and ground and flight test, the stakeholders on the team are exploring the tradespace to assist PEO Aviation in making informed decisions on future materiel upgrades and potential programs of record. This paper focuses on the initial analysis efforts to investigate the contributions of the various technologies to closing the TRADOC DVE capability gaps. The capstone event of the AMRDEC DVE Mitigation Program will be demonstration flights at Yuma Proving Ground in FY16 involving modernized flight control laws, multi-resolution sensor fusion, and varied cueing combinations.

Over the past 10 years, U.S. Army rotorcraft accidents due to DVE have resulted in 87 aircraft accidents (Class A and B) resulting in 108 fatalities and over $880M in material losses. Many of these losses were due to operations in "Brownout" (see Fig. 1).

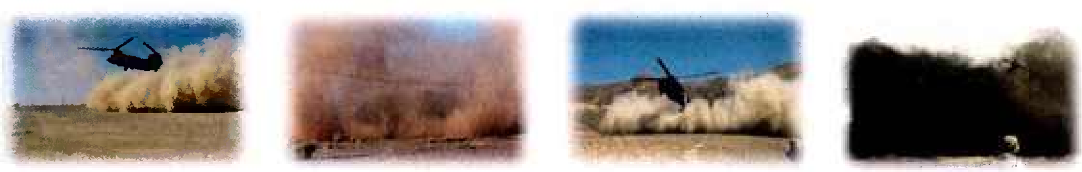

Fig. 1. Rotorcraft operations in brownout.

Although it may be accentuated due to the current theater of combat operations, DVE is more than just "Brownout" (helicopter induced dust cloud due to the downwash of the rotor system). Categories of DVE have been identified (Fig. 2) and accompanying data for potential future specification verification (e.g., "levels" of the different categories) has been identified (Fig. 3). Data exists for the other DVE categories, but only the brownout environment is illustrated and the accompanying analysis is primarily focused on brownout. However, a sensitivity analysis was also rapidly conducted to present a snapshot of results when the other environments in Fig. 2 are considered. Pursuit of materiel solutions will allow for not only the safe and efficient operation of rotorcraft but also expand the ability of commanders to deploy their rotorcraft aviation assets when the weather is well below minimum visual meteorological conditions. This objective is the basis for the mantra of the AMRDEC DVE Mitigation Program team: "Own the Weather"!

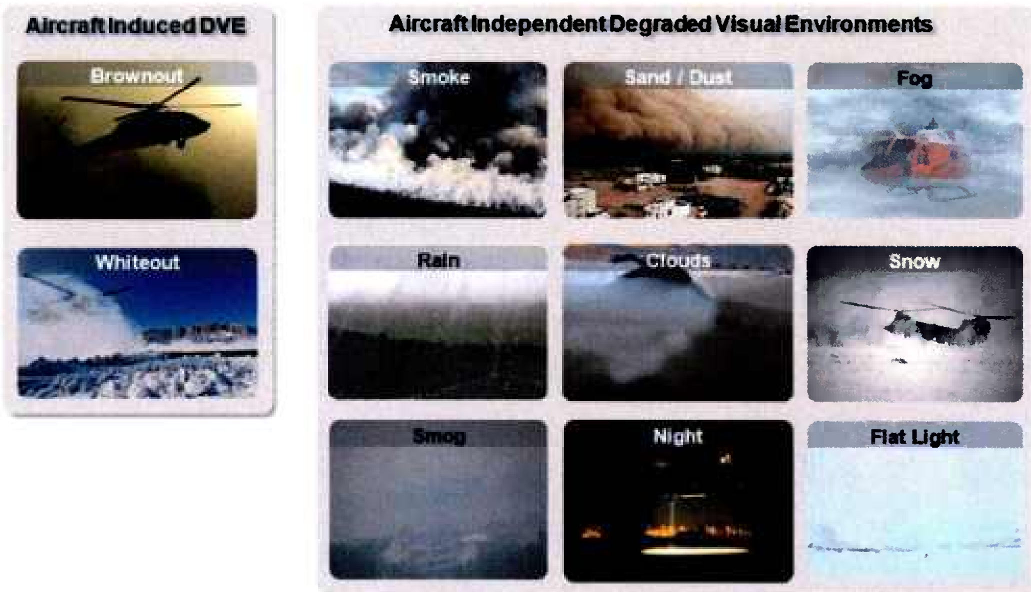

Fig. 2. Categories of DVE.

	Sand/Dust Storm	Aircraft Induced Brown-Out Sand/Dust R = 0 to 100 m	Aircraft Induced Brown-Out Sand/Dust R = 100 to 400 m
Light	0.01 g/m^3	0.5 g/m^3	0.5 g/m^3
Moderate	0.06 g/m^3	2.0 g/m^3	0.5 g/m^3
Heavy	0.27 g/m^3	3.5 g/m^3	0.5 g/m^3

Fig. 3. Characterization of the brownout environment utilized for this study.

Working with TRADOC, the definition of DVE was formalized for use by the Army rotorcraft community in 2012 as the following:

> *Reduced visibility of potentially varying degree, wherein situational awareness and aircraft control cannot be maintained as comprehensively as they are in normal visual meteorological conditions and can potentially be lost.*

Three Legs of the DVE Stool

Army officials view potential DVE system solutions as being comprised of three legs. In order to expand U.S. warfighting capability and conduct deliberate combat operations with Level 1 Handling Qualities (i.e., satisfactory, no improvement required) in DVE, all legs are necessary as no combination missing one or two leg(s) is sufficient. The three legs are:

1. *Improved Flight Controls*: Involves enhancing the existing flight controls systems and/or laws and handling characteristics to assist the pilot in managing workload when vision or situational awareness is challenged or obscured.
2. *Sensors*: Includes technologies that allow "see-through" capability when the environments in Fig. 2 are encountered.
3. *Cueing*: Comprises symbology, aural, or tactile indicators providing information to the pilot to reference aircraft state and potentially provide guidance for executing a mission task element (MTE) such as landing, take-off, or hover.

Stakeholders involved in exploring these three legs of the DVE stool include the AMRDEC Aviation Development Directorate [Aviation Applied Technology Directorate (AATD) and the Aeroflightdynamics Directorate (AFDD)], CERDEC Night Vision & Electronics Sensors Directorate (NVESD), AMRDEC System Simulation & Development Directorate (SSDD) and the Georgia Tech Research Institute (GTRI).

AMRDEC DVE Mitigation Program Objectives

The AMRDEC DVE Mitigation Program has four main objectives:

1. Develop an experimental plan using Design of Experiment techniques focused on examining contributions of different materiel technologies with regards to the eight TRADOC DVE capability gaps.
2. Provide detailed updates to pertinent specifications (e.g., ADS-33 (Ref. 1), MIL-STD-1787) with quantitative pilot-vehicle DVE operational performance data.
3. Baseline control system, sensor, and cueing technologies for possible off-ramp infusions into PEO Aviation programs of record.
4. Conduct and/or participate in flight demonstrations with numerous flight control, sensor(s) and cueing configurations.

Flight Controls

Overall, the Army considers the DVE challenge to rotorcraft to be a handling qualities problem and considers flight control augmentation to be a necessary part of the solution. The AMRDEC DVE Mitigation Program will examine control law upgrades, commonly referred to as MCLAWS, or Modernized Control Laws, that are exercised in the flight control computer (see Fig. 4). These upgrades may also include physical hardware (e.g. collective trim servo) and will result in improved handling qualities in accordance with the Army's handling qualities specification: Aeronautical Design Standard 33, or ADS-33 (Ref. 1). The addition of advanced inner and outer loop "modes" in the flight control system (e.g., attitude command/attitude hold, airspeed hold, height hold, heading hold, and position hold) will ultimately reduce the pilot's workload when operating in conditions of reduced visibility. With a more stable platform, the crew will then be better able to assess other concerns, e.g., approaching terrain and obstacles, potential landing area suitability and maintain improved situational awareness of overall aircraft state.

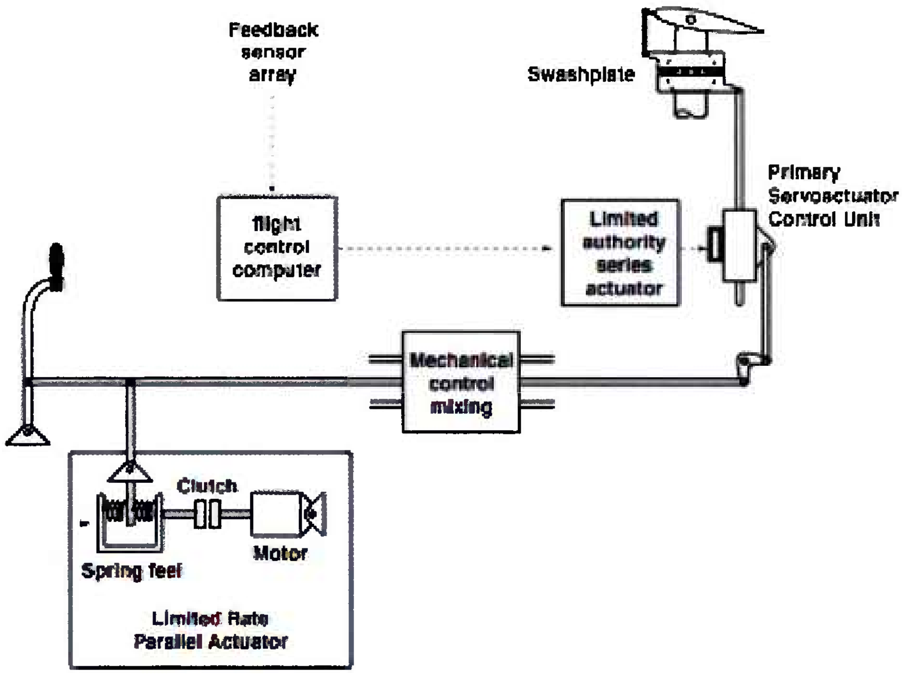

Fig. 4. Flight control system example.

Sensors

In the past, numerous sensor technologies have been studied and demonstrated, e.g., LADAR (Fig. 5), Millimeter Wave Radar (Fig. 6) and Infrared (Fig. 7). Overall, the "DVE community" has a good understanding of the enhancing capabilities as well as the shortcomings of each type of sensor, primarily in terms of penetration/range vs. resolution in different degraded visual environments. In order to achieve "see-through" capability in as many of the categories of DVE (Fig. 2) as possible, the AMRDEC DVE Mitigation Program is focusing on sensor fusion. A major part of the effort is better understanding the difficulty in integrating multi-resolution data sources (as well as a priori data) and balancing the trade-offs in imagery resolution that are required in presenting a cohesive "scene" during different flight modes (e.g. low level, contour, or nap of the earth (NOE) flight).

Fig. 5. Burns Engineering Corporation LADAR system as installed on ADD-AFDD EH-60L executing brownout landings at Yuma Proving Ground in June 2013.

Fig. 6. Sierra Nevada Corporation 94 GHz millimeter wave radar system as installed on ADD-AATD EH-60L executing flight test at Fort Eustis in May 2012.

Fig. 7. Raytheon Infrared Distributed Aperture System (DAS) as installed on CERDEC-NVESD UH-60A executing flight test at Fort Belvoir in March 2012.

Cueing

The AMRDEC team intends to execute two crew station working groups over the course of the program to explore the use of 3D (Fig. 8) and 2D (Fig. 9) symbology cueing overlaid upon imagery on both a panel mounted as well as a helmet mounted pilot medium. Individual sensor inputs will be emulated in the AMRDEC SSDD UH-60L simulator at Redstone Arsenal, Alabama. Additional cueing elements such as tactile and aural (Fig. 10) will be investigated to understand their potential value as a part of an integrated DVE system solution.

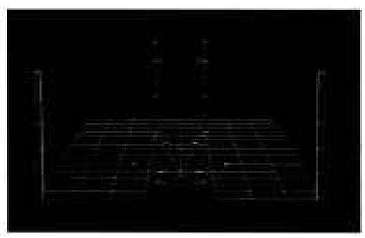

Fig. 8. 3D symbology cueing example.

Fig. 9. 2D symbology cueing example (overlaid on 94 GHz millimeter wave radar imagery with coincident day TV camera scene shown on right).

Fig. 10. Tactile and aural technology systems views.

Overall, the AMRDEC DVE Mitigation Program is oriented toward examining the combinations of required technologies that will give Army rotorcraft pilots the advantage on the battlefield. In total, this integrated three pronged approach to a DVE system solution is aimed at increasing aircrew safety and survivability while also helping to provide them every conceivable tactical and operational advantage. Through the use of a defensible decision support environment (DSE), the Army intends to take the first steps in executing a coherent test program to better understand the trade-offs between the available technologies that populate the three legs of the DVE stool.

Methodology

This methodology intends to produce a *defensible* DSE for selecting the most suitable set of technologies to mitigate the capability gaps for safe operations of rotorcraft in DVE. A decision is considered to be *defensible* if it can be justified with a rational and relevant argument. Rationality requires the process to be *transparent, traceable*, and *logical*, whereas relevancy requires the data supporting the process to be *accurate*, *current*, and derived from an *authoritative source*. A transparent and traceable process is one with a clear explanation for how it works—in this case, for how the rankings are determined—and one that allows reviewers to query the process and trace a decision throughout it. A logical process is one that agrees with the notions, experiences, and understanding of the reviewers. Such a process can be accomplished by involving a comprehensive set of subject matter experts (SMEs) from the beginning and having them vet it throughout. The SMEs should provide and update the data to ensure accuracy, currency, and validity. Following these guidelines, the DSE presented herein enables stakeholders to *produce defensible decisions* for meeting the capability gaps while operating rotorcraft in DVE.

The method outlined in this paper is based on Quality Function Deployment (QFD) (Ref. 2), Morphological Analysis (Ref. 3), and Multi-Attribute Decision Making (MADM) (Ref. 4) techniques. It leverages the basic concepts of QFD to integrate the knowledge of SMEs into a quantitative framework to identify the most promising DVE mitigation technologies. The value of these alternatives is assessed using MADM techniques to obtain a ranked preference and relative benefit of each alternative. The process strives to be customizable by leveraging the most suitable methods and techniques for the given application. The methodology described in this paper is an initial iteration based on the current understanding of the problem and the stakeholders' needs; it may be modified at a later stage based on improved understanding or an evolution in the requirements.

Integrating Expertise into the Decision Support Environment

The process of identifying promising technology combinations cannot be conducted in isolation; it requires the input of SMEs to (1) develop the structure of the framework and (2) provide the data necessary to perform the calculations. The success of the process is therefore predicated on the participation of accredited and knowledgeable SMEs. The ultimate goal is to integrate the topic-relevant information from the group of SMEs into a morphological matrix to effectively allow decision-making stakeholders to produce *traceable* and *defensible* decisions. To accomplish this specific goal, a diverse group of experts from government and academia were invited to participate in a series of workshops to define the problem, develop the framework, and provide their assessment on how well different technologies perform various functions.

Overview of the Process

The process is composed of four high-level phases. *Defining the problem* involves understanding the underlying needs, assumptions, constraints, and viable sets of alternatives that can be considered as potential solutions. *Defining the DSE framework* consists of identifying a set of mappings linking the technology options to the overarching needs. *Collecting and integrating data* involves not only the process of querying the SMEs, but also combining their know-how into a mathematical framework that properly captures their intent. *Leveraging this framework* is the final step by which all the work expended throughout the process produces actionable and defensible results. The knowledge gained at this final stage can inform updates to the other steps and can further strengthen and expand the framework.

Defining the Problem

Oftentimes, rapidly conducting this first step of the process may seem desirable as expending effort here may not appear to be contributing to any progress towards an answer. However, taking the time to fully define the problem is the most important step and helps flush out the true complexity as early as possible. This difficult step can lead to tedious arguments about the nuances of what the task at hand involves, e.g., what is and is not beyond the scope, what is the true underlying need. However, during this step, tacit assumptions about the problem are made explicit and an integrated understanding of the problem can be formalized. The result of the problem definition step may appear obvious and even trivial in hindsight, yet it is important to remember that the new definition of the problem most likely differs from the original form. Additionally, the problem definition may evolve as the problem itself is further refined through the process execution, but ideally, these changes will not considerably impact prior findings.

In this particular application, the TRADOC capability gaps for helicopters operating in DVE were recognized as a defensible set of goals. Nonetheless, the problem's definition had to be further refined in order to clarify the true need communicated by each of the capability gaps. Fig. 11 depicts and describes the eight gaps selected as the highest level objectives along with the inherent risk in not bridging that gap and the current capability to do so.

The next step is to bound the set of alternatives that can be used to mitigate these gaps. In this case, the scope of alternatives was not limited by aircraft type (i.e. the intent was to remain aircraft agnostic). The types of feasible individual technologies were then categorized into three main groups: Flight Controls, Real-time Sensors, and Cueing Systems. Flight Controls contains all the technologies that can be incorporated into a rotorcraft to facilitate its operation and impact the stability and/or control of the rotorcraft. Real-time Sensors includes all potential sensors that can organically gather data about the rotorcraft and its surroundings. The term 'organic' implies that the sensors cannot be dependent on transmitted data from other sensors or databases, except when using shared location information, e.g., Blue Force Tracker. Cueing contains all the technologies for displaying and conveying information to the pilot, including the various modes for transmitting information (e.g., visual, aural, tactile) and the symbology used for representing this information. In each group, all the technologies are defined in a system and vendor agnostic fashion.

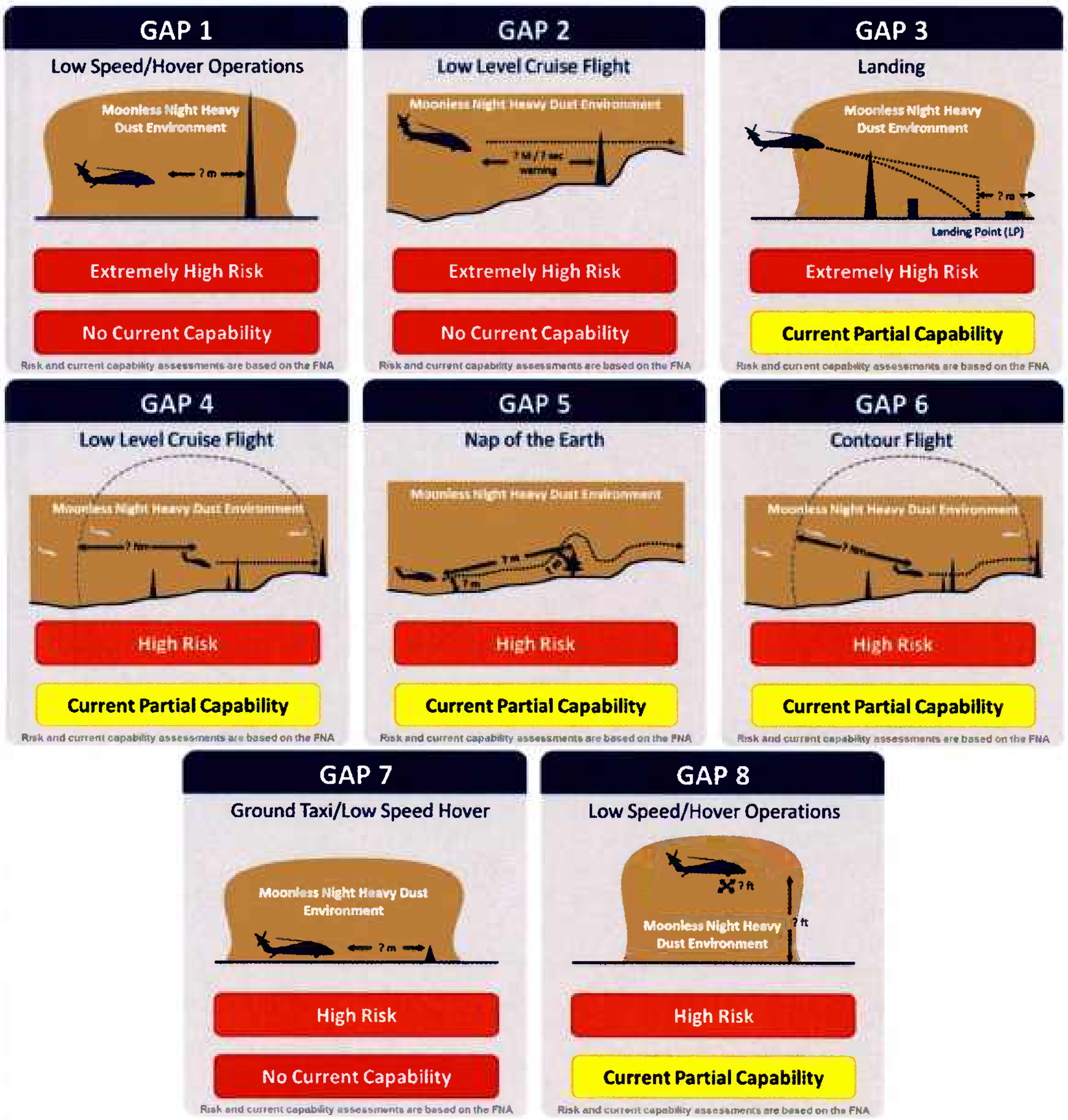

Fig. 11. Summary of the TRADOC capability gaps for rotorcraft operations in DVE (distances & times removed for OPSEC reasons).

Defining the Framework

The framework provides the basis for the organization of the data as it is this structure that defines how the data will be integrated and manipulated. The concepts presented here were inspired by QFD, a method for translating qualitative and subjective needs into quantifiable and measureable concepts.

The prior phase identified the capability gaps as the highest level goals and a series of DVE mitigation technologies as the set of viable alternatives that can be integrated to meet these goals. The next task consists of identifying a set of mappings that allow the stakeholders to trace the contribution of each alternative to the mitigation of the TRADOC DVE gaps. Since the technologies interact with one another, their contributions cannot be assessed independently and none provides a complete, feasible solution.

To provide a better mapping between broad gaps and specific technologies, intermediate steps are required. The first consists of decomposing the gaps down into the independent functions that must be achieved to bridge all gaps. The next consists of comparing the technologies and capturing all pertinent differential functionalities among them. Finally, the two sets of functions identified in these steps are united and refined over multiple iterations. Similar functions should be identified and specific differences reconciled.

The association between gaps and functions is modeled as how critical achieving a given function is in fulfilling a particular capability gap. The intent here is to capture how much of a dissatisfaction of the gap exists if a singular function is not achieved, e.g., even if all but one of the functions that are required to satisfy a gap are fully achieved, the gap still may not be achieved. This process is risk averse, as it avoids any compensation from achieving most, but not all, of the pertinent functions. The mathematical form of the satisfaction of a capability gap is then formulated as the complement of the maximum weighted dissatisfaction of the functions as illustrated by Equation 1 below:

$$Satisfaction\ of\ Capability\ Gap_j = 1 - \max_i\left(c_{i,j} \times (1 - s_i)\right) \tag{1}$$

where $c_{i,j}$ is the criticality of function i to capability gap j and s_i is the level of satisfaction of said function as mathematically defined below.

Similarly, the relationship between technology and function must capture how well different technological options achieve the functions in a specified environment. For this application, a specific, commonly encountered environment was agreed upon so that the elicited SME responses were formulated around a common baseline. The question posed to each SME is then how well each technology achieves each function in a heavy sand/dust environment at night. The satisfaction of a function i (s_i) can be calculated by identifying the enabled technology that satisfies the function to the highest degree, as defined below:

$$s_i = \max_k\left(s_{i,k} \times t_k\right) \tag{2}$$

where $s_{i,k}$ is the satisfaction of function i by technology k and t_k is a Boolean variable that indicates whether technology k has been selected, i.e., its value is 1 when technology k is selected, and 0 when it is not.

These functional satisfactions can be corrected for other environments through the use of a sensor-to-environment mapping table as the environment primarily affects the sensors. The relative performance of each sensor class is presented in Table 1. Using this mapping, the performance of the sensors can be corrected for a given environment of interest by multiplying the satisfaction of a sensor related function by their performance multiplier. For example, when looking at snow, the performance of EO/IR sensors will remain unchanged, but the performance of Radar and LIDAR/LADAR will be diminished slightly.

Table 1. Sensor performance in each DVE of interest.

Environment	EO/IR	LIDAR	MMWR
Smoke	M+	M+	N
Sand/Dust	N	N	N
Fog	M+	M+	N
Rain	N	M-	M-
Clouds	L+	M+	N
Snow	N	L-	L-
Smog	M+	M+	N

Legend: H+: Significant Improvement, M+: Moderate Improvement, L+: Minor Improvement, N: No Improvement, L–: Minor Detriment, M–: Moderate Detriment, H–: Significant Detriment

The overall structure of the process, i.e., the framework, is depicted in Fig. 12. It describes how six different pieces of information are integrated to generate viable combinations of technologies and trace their contribution to bridging the capability gaps.

1. A prioritization of the gaps using pairwise comparisons.
2. The mapping between functions and capability gaps.
3. A prioritization for functions based on the first two.
4. A mapping between technologies and functions.
5. A compatibility matrix for each technology.
6. A set of parameters that characterize the different technology alternatives.

The final product is a prioritized set of technology combinations. With the exception of products 2 and 4 which were defined previously, each one of these is described in detail below.

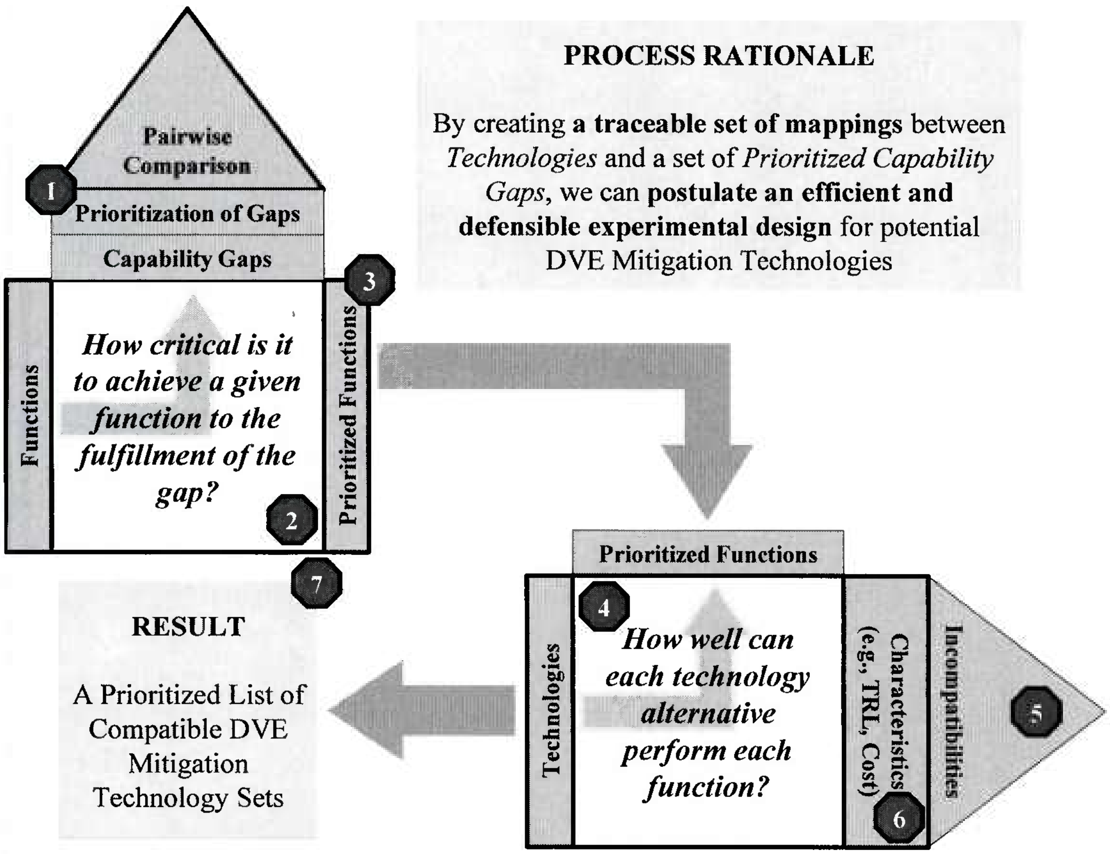

Fig. 12. Overview of the technology prioritization process.

It is clear that not all the gaps are equally important, as they impact different MTEs and involve different levels of risk. The problem of quantifying how important each one is relative to the others is not trivial, e.g., how can a SME ascertain that Gap 1 is 15% important and Gap 2 is 12% important. Nonetheless, pairwise comparison can be used to compare each one on a relative scale and obtain a normalized importance for each by synthesizing these relative relations. The process is similar to the one used in the Analytic Hierarchy Process (AHP) and relies on computing the principal eigenvector of the weighted adjacency matrix. The process and the importance of this vector are explained by T. L. Saaty (Ref. 5) in his seminal paper. Furthermore, the consistency of the votes can be mathematically computed to ensure that the pairwise comparisons are sensible, e.g., if the SME specifies that A is more important than B, and that B is more important than C, then A must be more important than C, otherwise, the vote would be inconsistent. The consistency metric can capture more refined levels of consistency across all pairwise comparisons, e.g., if A is twice as important as B, and B is three times more important than C, then A should be six times more important than C. The importance of the gaps is normalized using the 1-norm, meaning that their added importance equals 1.

Having prioritized capability gaps and a mapping relating gaps to functions allows for the prioritization of functions. This prioritization can be computed as the weighted sum of the criticality of each function using the capability importance as the weights, as defined below:

$$Importance\ of\ Function_i = \sum_j \left(c_{i,j} \times Importance\ of\ Gap_j\right) \tag{3}$$

where $c_{i,j}$ is the criticality of function i to capability gap j.

The last two products determine the technology specific parameters that limit the ability to select specific combinations. The compatibility matrix captures which technologies can be integrated, limiting the number of combinations the stakeholder can select. For example, if a particular display cannot represent a certain symbology, that information can be captured in the compatibility matrix and the combination of these two technologies is filtered out of the pool of viable combinations. The sixth and final product characterizes the cost of the technology, whether it may be monetary, based on the notion of risk, or based on the time it would take for that technology to become available. These characteristics serve as filters for the stakeholder.

Collecting and Integrating Data into the Framework

The data powering the framework was acquired during workshops and using surveys. Two workshops were facilitated at GTRI with the participation of SMEs from government and academia. The workshops served as an opportunity to discuss as a group different ideas and concepts and define the questions and the set of votes that would be elicited. The actual voting was done offsite through the use of surveys to maximize the efficiency of the group. The results were statistically studied to identify areas of scarcity and contradiction of votes. Due to the wide variety of disciplines involved, the SMEs were asked to vote on a mapping only if they were familiar and comfortable with the subject matter. Therefore, not all SMEs addressed all the technologies which led to certain mappings with a scarce number of votes. To remedy this situation, additional SMEs with expertise in these areas were invited to share their knowledge. In a few cases, there were statistical disagreements between the SMEs, but each one was reviewed and resolved to ensure the data in the framework is accurate and pertinent. Disagreements such as these often lead to a better understanding of the problem, as they highlight different points of view. Additionally, disparity could be an indication that the mapping is not properly defined or that it confounds various effects that should be separated and addressed independently.

Leveraging the Framework

The framework defined in the previous section can be leveraged to determine the best combinations of flight control, cueing, and sensor technologies to best address the DVE problem. The best technology combinations can be determined by using a cascading QFD approach to link the capability gaps to the individual technologies and then by using the morphological matrix to define all possible feasible technology combinations. The math for the cascading QFD is basic linear algebra that multiplies the capability gap to function score matrix, i.e., mapping, by the function to technology score matrix. The following equation summarizes the cascading QFD approach:

$$\overline{T} = TF \times \left(FC \times \overline{CW}\right) \tag{4}$$

where $\overline{T}$ is the vector of individual technology scores, *TF* is the technology to function scoring matrix, *FC* is the functions to capability gaps mapping (Table 2), and $\overline{CW}$ is the vector of capability gap weights.

Table 2. Functions to capability gaps mapping (numbers removed for OPSEC reasons).

Function Name \ Capability Gap Number	I	II	III	IV	V	VI	VII	VIII
Determine Location of Hazards at ? m	H	M	M	N	M	N	H	N
Determine Location of Hazards within ? m of landing point	N	N	M	N	N	N	N	N
Determine Location of Hazards within flight path	L	H	H	N	M	N	H	N
Determine Location of Forward Flight Hazards at ? m	N	N	N	M	H	M	N	N
Determine Location of Forward Flight Hazards at ? m	N	N	N	M	N	M	N	N
Determine Location of Forward Flight Hazards at ? m	N	H	N	M	N	N	N	N
Determine location of terrain and airborne hazards within ?° of the aircraft up to ? Nm	N	N	N	M	N	H	N	N
Determine location of terrain and airborne hazards within ?° of the aircraft up to ? Nm	N	N	N	H	N	N	N	N
Display Hazards	H	L	H	H	H	H	H	N
Provide Cueing of Aircraft State	H	N	M	N	N	N	M	H
Provide Precision Guidance	N	N	H	N	M	N	L	M
Convey Collision Warning	N	N	L	L	N	L	N	N
Convey Graduated Collision Warning	N	H	N	L	N	L	N	N
Determine LZ Slope	N	N	M	N	N	N	N	N
Display LZ Slope (Greater than ± ?°)	N	N	M	N	N	N	N	N
Provide Pitch/Roll Stability in Hover and Low-Speed Flight	H	N	H	N	N	N	H	H
Provide Pitch/Roll Maneuverability in Hover and Low-Speed Flight	H	N	M	N	N	N	H	H
Provide Yaw Stability in Hover and Low-Speed Flight	M	N	M	N	N	N	M	N
Provide Yaw Maneuverability in Hover and Low-Speed Flight	L	N	L	N	N	N	L	N
Provide Vertical Stability in Hover and Low-Speed Flight	M	N	L	N	N	N	M	N
Provide Vertical Maneuverability in Hover and Low-Speed Flight	M	N	M	N	N	N	M	N
Provide Position Control in Hover and Low-Speed Flight	M	N	M	N	N	N	H	H
Provide Maneuverability in Hover and Low-Speed Flight	L	N	M	N	N	N	H	H
Provide Pitch/Roll Stability in Forward Flight	N	N	N	N	M	H	N	N
Provide Pitch/Roll Maneuverability in Forward Flight	N	N	N	N	H	M	N	N
Provide Yaw Stability in Forward Flight	N	N	N	N	M	H	N	N
Provide Yaw Maneuverability in Forward Flight	N	N	N	N	H	M	N	N
Provide Vertical Stability in Forward Flight	N	N	N	N	M	H	N	N
Provide Vertical Maneuverability in Forward Flight	N	N	N	N	H	M	N	N
Augment Stability in Forward Flight	N	N	N	N	M	H	N	N
Augment Maneuverability in Forward Flight	N	N	N	N	H	M	N	N
Determine Absolute Positioning of the Aircraft	M	N	M	M	M	M	M	M

Legend: H: Significant Impact M: Moderate Impact L: Minor Impact N: No Impact

Given the vector of individual technology scores from Equation 4, the morphological matrix can then be used to determine the best combination of flight control, cueing, and sensor technologies. A feasible technology combination is generated by picking one technology from each of the subgroups and is scored by summing each of the scores from the chosen technologies. Using a morphological matrix to explore all possible, feasible technology combinations generally results in an intractable number of alternatives. Consequently, it is preferable to use an algorithm to find the "best" combination of alternatives. Oftentimes, evolutionary optimization algorithms are used for this purpose, but in this case, the technology combination scoring function is relatively simple and the alternative space is relatively small (approximately 56 million combinations), so it is possible to fully search the space to determine the top 10 alternatives. Fig. 13 presents the top 10 technology combinations identified by this search and provides insight into which technologies are categorically preferred by the algorithm and which are interchangeable, e.g., Position Hold in Hover/Low Speed Flight and LIDAR imaging modes, respectively.

Category	Group	Subgroup	Technology Option	Top 10 Technology Portfolios									
				P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_10
Flight Controls	Hover Low-Speed	Position	Hover Hold (HvrHld)	0	0	0	0	0	0	0	0	0	0
			Position Hold (PH)	1	1	1	1	1	1	1	1	1	1
		Yaw	Yaw Rate Command (RC)	0	0	0	0	0	0	0	0	0	0
			Direction Hold (DH)	1	1	1	1	1	1	1	1	1	1
		Vertical	Vertical Rate Command (RC)	1	1	1	1	1	1	1	1	1	1
			Height Hold (HH)	0	0	0	0	0	0	0	0	0	0
		Pitch/Roll	Rate Command / Attitude Hold (RCAH)	0	0	0	0	0	0	0	0	0	0
			Rate Command (RC)	0	0	0	0	0	0	0	0	0	0
			Translational Rate Command (TRC)	0	0	0	0	0	0	0	0	0	0
			Attitude Command / Attitude Hold (ACAH)	1	1	1	1	1	1	1	1	1	1
	Forward Flight	Yaw	Yaw Rate Command (RC)	1	1	1	1	1	1	1	1	1	1
			Direction Hold (DH)	0	0	0	0	0	0	0	0	0	0
		Vertical	Altitude Hold (HH)	0	0	0	0	0	0	1	1	1	1
			Vertical Rate Command (RC)	1	1	1	1	1	1	0	0	0	0
		Pitch/Roll	Rate Command/Attitude Hold (RCAH)	0	0	0	0	0	0	0	0	0	0
			Rate Command (RC)	0	0	0	0	0	0	0	0	0	0
			Attitude Command/Attitude Hold (ACAH)	1	1	1	1	1	1	1	1	1	1
Cueing	Pilot Vehicle Interface	Visual	Panel Mounted Display	1	1	1	1	1	1	1	1	1	1
			Narrow FOV with Head Tracking Display	0	0	0	0	0	0	0	0	0	0
			Narrow FOV without Head Tracking Display	0	0	0	0	0	0	0	0	0	0
			Wide FOV with Head Tracking Display	0	0	0	0	0	0	0	0	0	0
			Wide FOV without Head Tracking Display	0	0	0	0	0	0	0	0	0	0
		Audio Projection Mode	Mono Audio	0	0	0	0	0	0	0	0	0	0
			Stereo Audio	0	0	0	0	0	0	0	0	0	0
			3-D Audio	1	1	1	1	1	1	1	1	1	1
	Terrain/ Obstacle Imagery	Scene Imagery	Fused Imagery	1	1	1	1	1	1	1	1	1	1
			Enhanced (Sensor Only)	0	0	0	0	0	0	0	0	0	0
			Synthetic (Database Only)	0	0	0	0	0	0	0	0	0	0
	Symbology		3D Terrain Conformal Symbology	1	1	1	1	1	1	1	1	1	1
			Conventional 2D Aircraft PFR Symbology	0	0	0	0	0	0	0	0	0	0
Real-time Sensors	LIDAR/LADAR	Detection Mode	Geiger Mode Detection	0	0	1	1	0	0	0	1	0	1
			Heterodyne Detection	1	0	0	0	1	0	0	0	1	0
			Direct Detection	0	1	0	0	0	1	1	0	0	0
		Imaging Mode	No LIDAR/LADAR	0	0	0	0	0	0	0	0	0	0
			Scanning LIDAR/LADAR	0	0	0	1	1	1	0	0	0	1
			Flash LIDAR/LADAR	1	1	1	0	0	0	1	1	1	0
	Passive/Active Imaging		No Imager	0	0	0	0	0	0	0	0	0	0
			Millimeter Wave Imager	0	0	0	0	0	0	0	0	0	0
			Long Wave Infrared Imager	1	1	1	1	1	1	1	1	1	1
			Medium Wave Infrared Imager	0	0	0	0	0	0	0	0	0	0
			Short Wave Infrared Imager (Illuminated)	0	0	0	0	0	0	0	0	0	0
			Visible/Near Infrared Imager	0	0	0	0	0	0	0	0	0	0
	Radar	Frequency	No Radar	0	0	0	0	0	0	0	0	0	0
			Ku Band (12 to 18 GHz)	0	0	0	0	0	0	0	0	0	0
			X Band (8 to 12 GHz)	0	0	0	0	0	0	0	0	0	0
			W Band (75-110 GHz)	1	1	1	1	1	1	1	1	1	1
			Ka Band (26.5 to 40 GHz)	0	0	0	0	0	0	0	0	0	0
		Mode	Real Beam Radar	1	1	1	1	1	1	1	1	1	1
			Synthetic Aperture Radar	0	0	0	0	0	0	0	0	0	0
	Precision Geopositioning		Inertial Navigation System (INS)	0	0	0	0	0	0	0	0	0	0
			Global Positioning System (GPS)	0	0	0	0	0	0	0	0	0	0
			Embedded GPS/INS (EGI)	1	1	1	1	1	1	1	1	1	1

Fig. 13. Top 10 technology portfolios identified by the study.

Results

The framework can be queried in a myriad of different ways to *discover* new information that was not apparent in the original data. This requires a certain degree of creativity and a high degree of mathematical rigor to avoid drawing inappropriate conclusions. Below is a description of additional results that can be gleemed from the DSE.

In addition to identifying the preferred individual technologies, or combinations thereof, the framework can give an indication of how much each category of technologies contributes to the overall bridging of the gaps. This is important because it prioritizes the groups of technologies and informs the stakeholders as to which solution sets should be researched further. Analyzing the maximum value of each technology, as calculated by deploying the capability gap importance through the two mapping matrices, it is possible to estimate how important each technology alternative is. Using these values for each sub-category, one can estimate the average maximum contribution from each sub-group for each category, i.e., an indication of how much each group of technologies can contribute to bridging the eight capability gaps. Fig. 14 depicts the results showing that 46% percent of the contribution is provided by the sensors, while 39% is provided by the cueing systems, and 15% by the flight controls. This agrees with the concepts defined in ADS-33 (Ref. 1), whereby the addition of sensors and cueing would improve the Usable Cue Environment (UCE) and improved flight controls would attain the required level of handling qualities. In addition to this conclusion, this figure shows that no single group of technologies can address all the gaps. The DVE solution must leverage technologies from each one of these groups.

It must be pointed out that many assumptions and assertions were identified by the subject matter experts on the team prior to their "scoring" iteration. These were necessary in order to present coherent scenarios and metrics that could be scored without bias. Additionally, the TRADOC capability gaps utilized were the basis that the experiment was formed around; the gaps are somewhat "imaging centric" and a revised/expanded set of capability gaps would most assuredly result in different outcomes/percentages. Finally, it must be noted that all elements of the DVE system material solution (the 3 legs of the stool) are essential as no one or two leg(s) can provide the objective endstate of an aircraft being able to expand its operational maneuver space by executing combat operations in degraded visual environments with Level 1 handling qualities throughout the flight envelope.

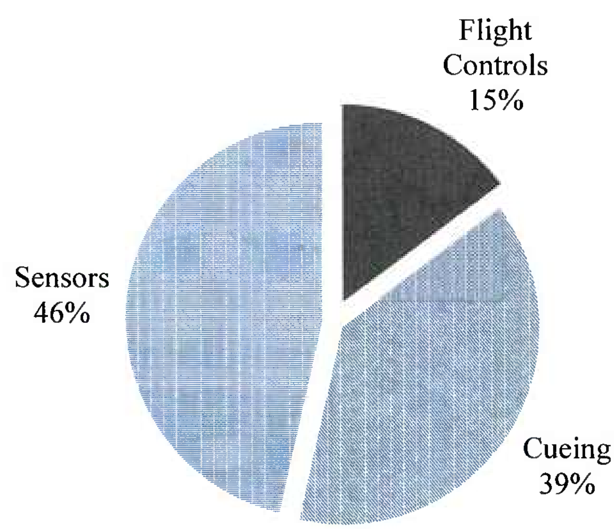

Fig. 14. Average maximum contribution of each technology sub-category.

Conclusions

The paper outlines the development of a framework to support decision-makers tasked with developing an experimental plan for DVE mitigation technologies. The process traces the alternatives to the highest level goals, and allows decision makers to not only obtain a ranked set of combinations to test based on how well they address these high level needs, but it allows them the *transparency* and *traceability* of querying the framework and tracking the operations performed by the DSE. The data, and the structure of the process, was not developed in isolation, but with the assistance and guidance of a broad group of SMEs from government and academia. This ensured that their experiences and opinions were reflected not only in the data they provided to populate the DSE, but also in its architecture and logic and ultimately, the results generated. The final product is a *logical* series of calculations that mathematically capture the SMEs' rationale and allows decision makers to query the DSE without having to independently query the SMEs on every combination of technologies. In essence, the environment serves as a surrogate of the SMEs' combined experience and know-how on the subject. This makes the process *rational*, and, combined with the ability of the framework to incorporate *relevant* information, makes the overall decision *defensible*.

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List of Figures

List of Tables