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Quantifying Capability Vectors

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Abstract

The analysis process through the years has progressed to see the evolution of measurable and observable metrics. Trying to enhance the process is an ongoing endeavor and pursuit. Recently, the work has been focused on tailoring system analysis output metrics for input into end-game simulations. The concepts introduced in this report will attempt to address this issue; these concepts include (1) the quantification of capability vectors, (2) capability granularity, and (3) capability networks.

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1. Introduction

The analysis process through the years has progressed to see the evolution of measurable and observable metrics. Trying to enhance the process is an ongoing endeavor and pursuit. Recently, some work has been focused on tailoring system analysis output metrics for input into end-game simulations. The concepts introduced in this report will attempt to address this issue; these concepts include (1) the quantification of capability vectors, (2) capability granularity, and (3) capability networks.

2. Background

The vulnerability/lethality (V/L) process was envisioned to be a series of mappings and spaces (Deitz and Ozolins 1989). Klopcic, Starks, and Walbert (1992) formalized this process, discussing the scientific process behind V/L analysis and introducing the V/L taxonomy shown in Figure 1. Walbert (1994) addressed the concept of granularity within the V/L analysis process. As Walbert mentions in his report, one can generate information at any level within the analysis process at any given time. This concept allows one to denote the specific times at which information is gathered at each level. Walbert identifies the desired levels of granularity with regard to the analysis inputs as well as the geometric target description. At Level 1, the type of analysis usually sets the pace of the level of granularity of the inputs and determines the level of effort. Once all the pertinent files are generated, the analysis and information gathering begin. Next, embedded in Level 2 is a list of components damaged by the threat mechanism. Each of these critical components is assigned a table that yields a probability of component dysfunction given a hit ($P_{cd/h}$). In the current methodology, this empirically derived number is then compared to a random number draw between 0 and 1 inclusive. If this random number is equal to or greater than the respective $P_{cd/h}$, then the component is killed (a binary 0 is assigned). If the $P_{cd/h}$ is less than the random variable, the component is fully functional (a binary 1 is assigned). Once every critical component is assessed, the functionalities of the components are used to determine Level 3 metrics via capability/fault trees or engineering

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VL0 (Level 0) — Threat Event

$O_{0,1}$ **Mapping** — Physics

VL1 (Level 1) — Initial Conditions

$O_{1,2}$ **Mapping** — Physics

VL2 (Level 2) — Damage/Degradation State

$O_{2,3}$ **Mapping** — Engineering

VL3 (Level 3) — Capability State

$O_{3,4}$ **Mapping** — Mission Scenario

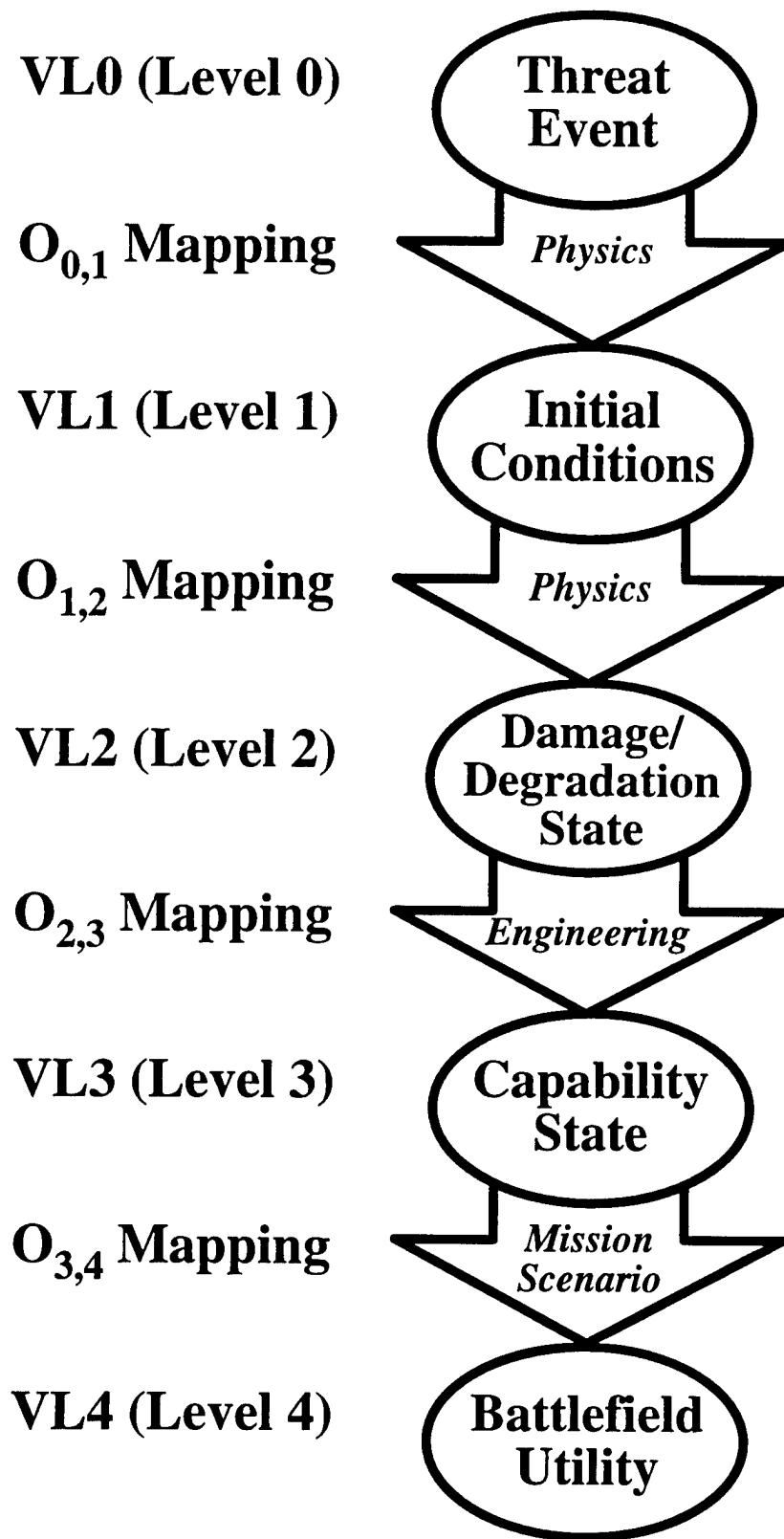**VL4 (Level 4)** — Battlefield Utility

Figure 1. The V/L Taxonomy.

performance models (EPMs). Capability/fault trees are logical constructs of component functionality consisting of serial and parallel paths (Boolean AND/OR operations). These trees, once evaluated, will yield a capability. An EPM is an engineering-based computer model on engineering principles or empirical data that outputs engineering subsystem or system performance. This information is then processed, and the remaining system or subsystem capabilities are established.

In the same report, Walbert talks about an instance of time-varying states within one snapshot in time. Time is more a factor within the chemical and biological arena than in the ballistic arena.[*] The instantaneous damage due to a ballistic encounter is measured in terms of seconds. However, the damage due to a chemical or biological threat could (and does) take minutes, hours, and maybe days, not to mention the decontamination process. The initial V/L process structure that was devised from the ballistic point of view had to be modified. Thus, the V/L process structure was modified and expanded by Ruth and Hanes (1996) to present the chemical, biological, and nuclear process. With the evolution of the V/L time-discrete process structure comes a method to implement multivalued (as opposed to binary) component functionalities and the resultant capability measures.[†] This leads to the idea of quantifying the capability vectors within the process structure. Section 3 will discuss quantifying capability vectors in more detail. All of these new concepts will be encompassed in capability networks ($O_{2,3}$ mapping), as mentioned in Ruth and Hanes (1996). A capability network can be extended in order to address varying capability levels. A capability network also addresses the resolution of Level 2 component functionality metrics. Even though the V/L analysis technically stops at Level 3, this new concept has great value as it continues the V/L process structure into Level 4. This is observed by stepping through the lower levels of capability granularity. Within the context of this report, for the sake of clarity, the terminology will be stated in terms of the V/L taxonomy (rather than the terminology of the V/L time-discrete process structure).

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[*] Time is a factor within the ballistic arena when the threat produces fuel, oil, and hydraulic fluid leaks.
[†] It is realized that time is not the only factor when determining multivalued component functionalities. For conventional ballistics, it is the ability to measure less than 100% functionality.

Also, the initial V/L process structure (designed specifically within the context of a ballistic V/L analysis) assumed that analyses commenced at the threat/target interaction level (Level 1). Thus, a separate level was added to account for the initial fly-out of the threat to model the likelihood of the threat encountering the target. This collection of initial threat event configurations is known as Level 0, while the $O_{0,1}$ mapping evolves threat vectors from initial configurations, which will determine the Level 1 state, leading to the first moment of target system interaction ($O_{1,2}$).

3. Quantifying Capability Vectors

The concept of quantifying capability categories has not been a critical issue in regard to ballistic vulnerability. For ballistics, once the threat/target interaction has taken place, an impacted component is either functional or nonfunctional. There was no immediate need to have a partially functional capability. Now, when discussing the integration of capabilities to cover all battlefield threat areas of concern to the Survivability/Lethality Analysis Directorate (SLAD), the need for partial capability is more acute.

3.1 Ability to Illuminate at Night. Consider the capability ability to illuminate at night. The components that enable this capability are a 12-V dry cell battery, a lightbulb, cables, and an on/off switch. The battery is hooked to the lightbulb by conducting cables. The cables electrically connect the battery to the lightbulb, with the on/off switch connected in-between to control the flow of current, as illustrated in Figure 2. The battery consists of six cells connected in parallel, where each cell provides a potential difference of 12 V and a rated current of 10 Ah. This produces a total available source current I_S of (10 Ah/cell) * (6 cells) = 60 Ah. In other words, I_S is the sum of the individual source currents I_{Sn} from the dry cells, where n = 1,2,3,4,5,6. Now, the battery can be divided into seven different normalized functional values ranging from 0 to 1, as summarized in Table 1. If we assume that each of the six cells is either functional or nonfunctional, then we have six different levels of battery functionality. From a ballistic point of view, a bullet could pierce any one of the six cells, causing the cell to lose its electrolytic fluid and result in an open node within the circuit, thus reducing I_S by 10 Ah per damaged dry cell. Finally, each succeeding cell that is drained
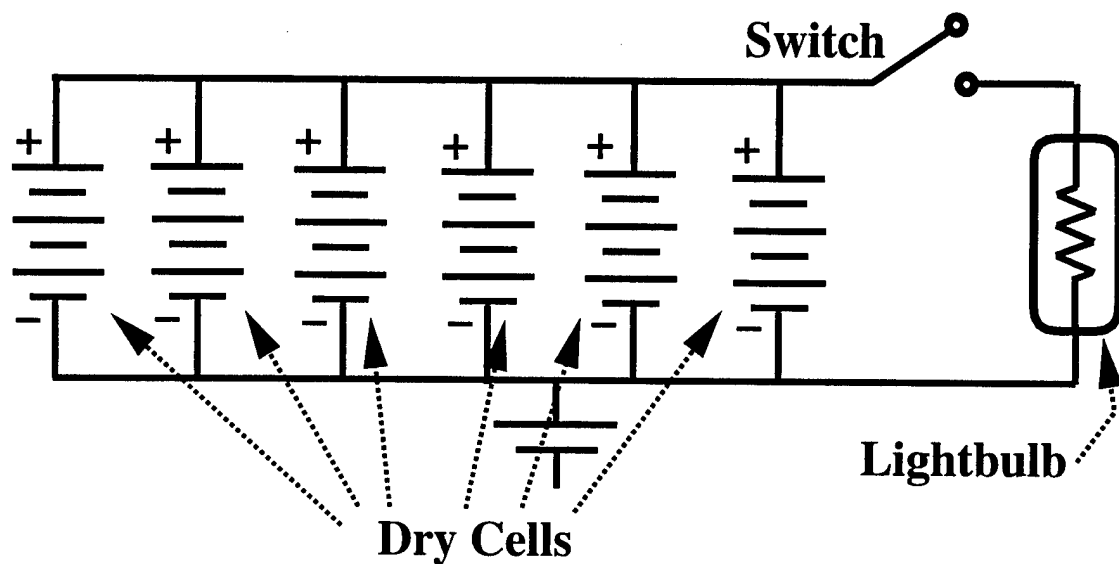
Figure 2. Components Which Enable the Capability Ability to Illuminate at Night.

Table 1. Battery Functionality $F_{Battery}$ and the Resultant Ability to Illuminate at Night Capability $C_{Illuminate}$

Battery Current (Ah)	$F_{Battery}$	Lightbulb Rated Power (Wh)	$C_{Illuminate}$
0	0	0	0
10	0.167	11.2	0.366
20	0.333	19.3	0.631
30	0.5	24.0	0.784
40	0.667	27.0	0.882
50	0.833	29.1	0.951
60	1.000	30.6	1.000

by a bullet will reduce the current available to drive the lightbulb by 10 Ah and will accordingly reduce lightbulb rated power $P_{lightbulb}$ according to the equation

$$P_{lightbulb} = V_{lightbulb} * I_{lightbulb}, \qquad (1)$$

where $V_{lightbulb}$ and $I_{lightbulb}$ are the voltage across and current within the lightbulb, respectively, and R_S is the source resistance of the entire dry cell battery, where

$$R_s = \frac{1}{\left[\sum_{n=1}^{6} \left(\frac{1}{Rn} \right) \right]}. \qquad (2)$$

Combining equations (1) and (2), we get

$$P_{lightbulb} = I_s^2 \left(\frac{R_s}{R_s + R_{lightbulb}} \right)^2 R_{lightbulb}. \qquad (3)$$

If we assume the source resistance of the nth cell is equal to 0.45 Ω and $R_{lightbulb}$ = 0.50 Ω, then the relationship between discrete levels of battery functionality and lightbulb rated power $P_{lightbulb}$ (the Level 3 metric we use to measure the capability ability to illuminate at night) is further summarized in Table 1. (For a similar example, see Ruth and Hanes [1996]).

3.2 Ability to See a Distance of 1/2 Mile. Next, let us study the case of a soldier in a chemical warfare environment, where the capability of interest is the ability to see a distance of 1/2 mile. For instance, a soldier may develop miosis after encountering a chemical agent. Miosis is an eye disorder in which the pupil contracts, limiting the amount of light into the eye, therefore limiting sight. The baseline metric, perfect vision, in this case will be 20/20 vision. The amount of chemical agent absorbed by the soldier, along with his physiology will account for the levels of visual degradation. Now, based on hypothetical experiments performed by applying eyedrops directly on the eye, the following levels hold true. The levels of degradation to eye function will be divided

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among 10 levels, ranging from 20/20 vision (eye function = 1) to 20/110 vision (eye function = 0), where 20/20 = perfect vision and 20/110 = loss of vision.

3.3 Ability to Process Incoming (and Export Outgoing) Information. Finally, consider the case of an electromagnetic pulse (EMP) vs. electrical/electronic components. Let's examine the case where a black box carries information over a 20-line data bus. The associated capability would be the ability to process incoming (and export outgoing) information. When an EMP penetrates the black box, it damages several lines on the bus, thus allowing only partial information through to be processed and exported. So, the metric in this case is similar to the battery case in that every line has the potential to carry information; therefore, the range of this metric will be from 0 to 1, in increments of 20. Note, the point here is that some capabilities can be defined at a very detailed level, to better emulate that the real but many capabilities are binary past a certain threshold level when struck by a ballistic threat.

3.4 Fuel System of a Generic Military Helicopter. To illustrate this last point, let's discuss the fuel system of a generic military helicopter. Take the case of a high-energy armor-piercing incendiary (API) that enters the aircraft and also the rear fuel tank, causing the atomized fuel to ignite with the incendiary. In one case, the transient response of this action is instantaneous and an explosion occurs bypassing any threshold level, making it a binary choice of a kill. In a second case, the API, for some reason, does not ignite with the fuel resulting in a hole in the tank that leads to a leak. The transient response in this case is substantially longer, allowing the aircraft to operate in a degraded state. After some period of time, if the aircraft has not landed, it will eventually lose fuel (pass the existing threshold) and possibly result in loss of the aircraft.

4. Concept of Capability Granularity

4.1 Capability Networks. Ruth and Hanes (1996) mentioned that for a subsystem consisting of n components connected together in serial, so that each is essential for the operation of the subsystem, the resultant subsystem-level capability is the output of a chain of transfer functions that

pass a "resource" through a network formed by the components. Thus the output capability metric is a function of all component functionalities, so that

$$C = F_{COMPn} (F_{COMPn-1} (F_{COMPn-2} (...F_{COMP2} (F_{COMP1})...))), \quad (4)$$

which is read as "capability C is a function of the functionality of the nth component F_{COMPn}, which itself is a function of the functionality of the (n-1)th component $F_{COMPn-1}$, which is a function of...the functionality of the second component F_{COMP2}, which is finally a function of the functionality of the first component in the network F_{COMP1}." Each of these component functionalities is a combination or rollup of both a component's independent and dependent functionalities. This is the basic blueprint for a capability network. In a similar fashion, subsystem-level capability metrics can be networked together to produce system-level capabilities. In this construct, capabilities associated with subsystems of approximately equal granularity levels interact with each other to produce a capability of lower-level granularity. Let us first define what is meant by low-level and high-level granularity. Think in terms of a pyramid, or in this particular report, an inverted pyramid. With an inverted pyramid structure, all of the high-level granularity (many, small granules) will be at the top and it would funnel down to the lower-level granularity (fewer, larger granules). A graphical example of the inverted pyramid showing high-level granularity flowing down to low-level granularity is given in Figure 3. As in a network of interacting components, resource flow through a network of capabilities can also occur in a serial progression from capability to capability.[*] Thus, for a linear network, we can express a low-granularity capability as a function of m serially linked capabilities through the expression

$$C^{m-1} = \prod_{k=1}^{k=n} C_k^m, \quad (5)$$

where C^m and C^{m-1} are dimensionless capabilities (normalized to optimal subsystem performance metrics) of granularity levels m and m-1, respectively. Thus, if we define $C^m = C^{MAX}$ as a capability

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[*] Of course, resources can also flow in parallel; however, there is always some point in the network where these parallel resources are added or joined together.

M14

M10 M11 M12 M13

M1_LF M2_LF M3_LF M4_LF M5_LF M6_LF
M7_LF M8_LF M1_RT M2_RT M3_RT M4_RT
M5_RT M6_RT M7_RT M8_RT M9

Structural
Integrity

Flight Controls

Powerplant/
Power
Distribution
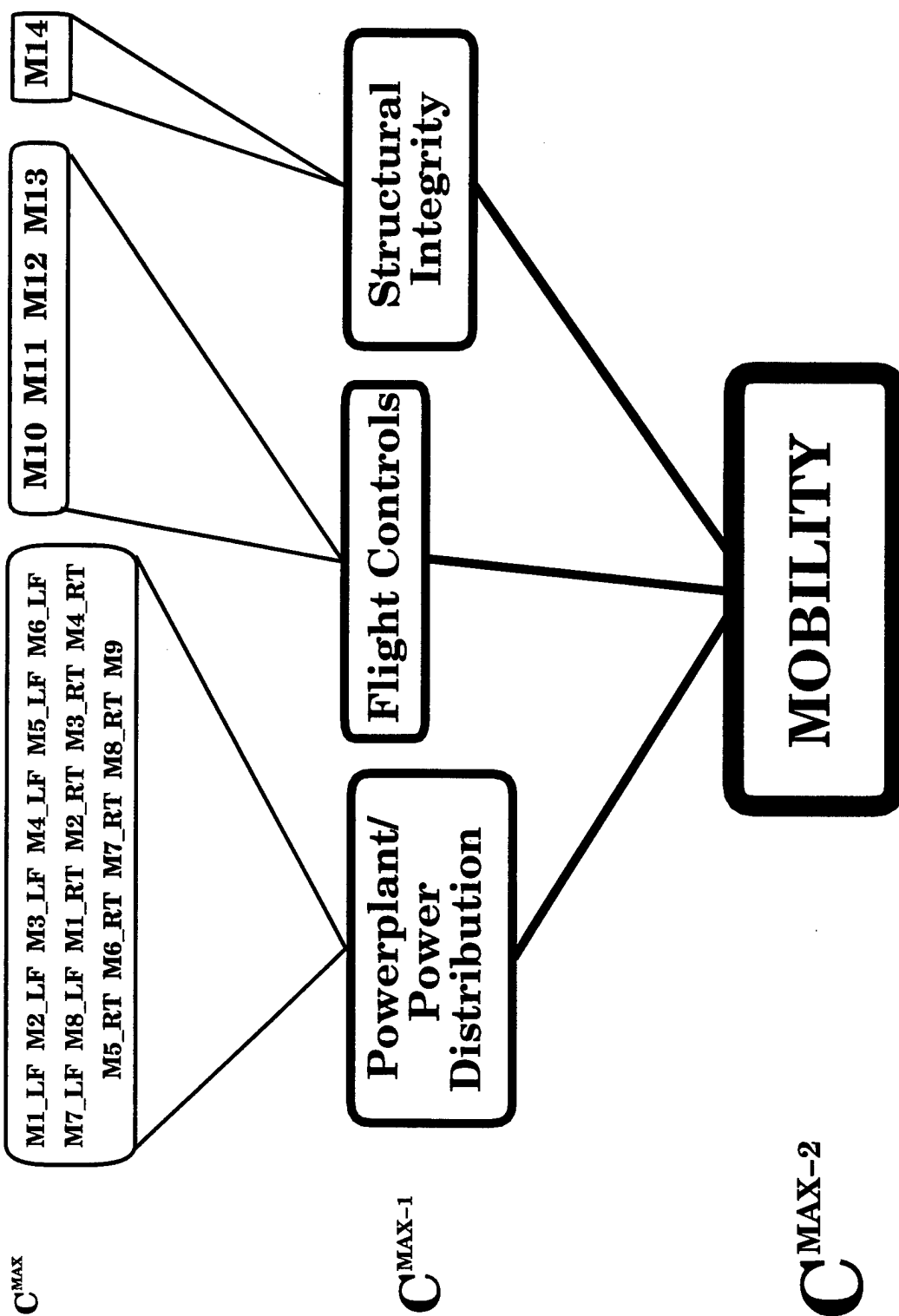
MOBILITY

C^{MAX}

C^{MAX-1}

C^{MAX-2}

Figure 3. Varying Levels of Ability to Move Capability Granularity for a Generic Military Helicopter.

of atomic (maximum resolution) granularity level and $C^{m-1} = C^{MAX-1}$ as a capability defined at a lower granularity level, then equation (5) becomes

$$C^{MAX-1} = C_1^{MAX} * C_2^{MAX} * C_3^{MAX} * ... * C_n^{MAX}. \tag{6}$$

This mapping is similar to the logical product (Boolean AND) of n components within a capability tree and will be applied to the helicopter powerplant/power distribution capability network discussed in section 4.2.

Figure 3 also illustrates the concept of varying levels of capability granularity as applied to the ability of a generic military helicopter to move. A total of 22 mobility-type capabilities of the helicopter are defined at granularity level C^{MAX} (the highest or atomic level of capability); each of these 22 capabilities is itself produced by synergism within a network of components. Then, these C^{MAX} level capabilities are networked "down" to the C^{MAX-1} granularity capabilities "engine power and delivery," "flight controls," and "structural integrity" (note that, in the last case, $C^{MAX-1} = C^{MAX}$). Finally, these coarser-grained capabilities are networked together to result in the system-level capability ability to move, where $C^{system} = C^{MAX-2}$. The capability network, which maps 17 of the above "atomic-level" capabilities, is discussed in section 4.2, while the process of mapping from the C^{MAX-1} to the C^{MAX-2} level is discussed in section 4.3.

As seen in Figure 3, a low-level analysis can begin at the C^{MAX-2} granularity level. Low levels of granularity can grow from the idea of a concept system, a system of which we have no intelligence information (foreign) or just a low-detail analysis. Low-detail analyses of a combat utility system could simply consist of the three basic properties: ability to move, ability to operate, and ability to communicate. These now become the capability categories. It may only consist of the first two, if, and only if, there is no reason to communicate to complete the mission. One problem with a low-detail analysis is that a capability metric, such as ability to move, is usually represented by one number (a scalar). The mobility capability of a real system, such as a helicopter, would actually be represented by a vector of a form similar to ability to cruise forward/backward, ability to

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ascend/descend, ability to hover, or ability to change direction leftward/rightward. This concept will be further discussed in section 4.3.

4.2 Powerplant/Power Distribution Capability Network. In order to illustrate the concept of capability networks and how they apply to varying levels of capability granularity, we will examine the ability-to-move capability of the generic military helicopter mentioned in the previous section. Seventeen of the atomic capability metrics (granularity level MAX), which define the powerplant/power distribution capability within the helicopter (granularity level MAX-1), are described in Table 2.* Each of these seventeen capabilities is realized by the functioning of one or more components, such as, M7_RT, the ability to maintain power extraction from the right engine, which is produced by interaction between the right engine power turbine, the right engine output shaft, and the right engine exhaust. Once each of the 17 capabilities of maximum granularity level (C^{MAX}) is established, they can be networked together to produce and distribute engine power within the helicopter (C^{MAX-1}). However, in order to properly model a network, the resources that flow between the capabilities must also be identified; these resource metrics are described in Table 3. Finally, Table 4 lists several other metrics required to formulate the powerplant/power distribution capability network.

Once we have identified all of the required elements, we can construct the powerplant/power distribution capability network. A graphical representation of the network is illustrated in Figure 4. Following the flow through the network for the left engine (LF), first, fuel is pumped from the fuel tank to the left engine (**M1_LF**). Degradation to this capability would result in a reduced rate of pumped fuel/time unit, which would also lower the fuel pressure, since

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{dm_{fuel}}{dt} * \frac{v_{fuel}}{\text{Area}}, \tag{7}$$

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* The three levels of granularity mentioned above are specific to this engineering application. It is realized that one could have more levels of granularity associated with it.

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Table 2. The 17 Capabilities That Interact to Produce and Distribute Engine Power Within the Helicopter. The Capability Metrics Are Normalized to Design Optimal Performance Levels in the Case of M3_LF, M3_RT, M7_LF, M7_RT, and M9

Metric	Description	Possible Values
M1_LF	Ability to deliver fuel to the left engine.	0, 1
M1_RT	Ability to deliver fuel to the right engine.	0, 1
M2_LF	Ability to deliver oil to the left engine.	0, 1
M2_RT	Ability to deliver oil to the right engine.	0, 1
M3_LF	Ability to maintain airflow for the left engine. M3_LF = airflow rate/15 lb/s.	$0 \le M3\_LF \le 1$
M3_RT	Ability to maintain airflow for the right engine. M3_RT = airflow rate/15 lb/s.	$0 \le M3\_RT \le 1$
M4_LF	Ability to maintain compression for the left engine.	0, 1
M4_RT	Ability to maintain compression for the right engine.	0, 1
M5_LF	Ability to maintain combustion from the left engine.	0, 1
M5_RT	Ability to maintain combustion from the right engine.	0, 1
M6_LF	Ability to maintain expansion from the left engine.	0, 1
M6_RT	Ability to maintain expansion from the right engine.	0, 1
M7_LF	Ability to maintain extraction from the left engine. M7_LF = power/1,500 shp.[a]	$0 \le M7\_LF \le 1$
M7_RT	Ability to maintain extraction from the right engine. M7_RT = power/1,500 shp.	$0 \le M7\_RT \le 1$
M8_LF	Ability to maintain electrical power from the left engine.	0, 1
M8_RT	Ability to maintain electrical power from the right engine.	0, 1
M9	Ability to transfer mechanical power through the fuselage. M9 = (engine_power * transfer coefficient)/design optimal power = (engine_power * 0.95)/3,000 shp.	$0 \le M9 \le 1$

[a] Shaft horsepower = shp.

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Table 3. Resource Metrics Involved in the Production and Distribution of Engine Power Within the Helicopter

Metric	Description (Units)	Possible Values
LF_air_flow	Mass rate of airflow into the left engine (lb/s).	$0 \leq$ **LF_air_flow** ≤ 15 lb/s
RT_air_flow	Mass rate of airflow into the right engine (lb/s).	$0 \leq$ **RT_air_flow** ≤ 15 lb/s
LF_power	Power extracted from the left engine (shp).	$0 \leq$ **LF_power** $\leq 1,500$ shp
RT_power	Power extracted from the right engine (shp).	$0 \leq$ **RT_power** $\leq 1,500$ shp
engine_power	Total extracted engine power (shp).	$0 \leq$ **engine_power** $\leq 3,000$ shp
main_rotor_power	Power transferred to main rotor (shp).	$0 \leq$ **main_rotor_power** $\leq 2,850$ shp

Table 4. Other Metrics Associated With the Production and Distribution of Engine Power Within the Helicopter

Metric	Description	Possible Values
time_no_oil	Time interval of engine operation without oil.	$0 <$ time_no_oil < 30 min
LF_air_pressure_sensor	Functionality of the left engine air pressure sensor.	0, 1
RT_air_pressure_sensor	Functionality of the right engine air pressure sensor.	0, 1

where dm_{fuel}/dt = mass rate of fuel flow and v_{fuel} = fuel fluid velocity. A reduction in dm_{fuel}/dt is equivalent to a reduction in pumped fuel/time unit; thus the fuel pressure is lowered. In a parallel process, ambient-temperature air flows into the engine (M3_LF). Degradation to this capability would result in a reduced rate of moving air volume/time unit, which, as with the fuel pressure, will

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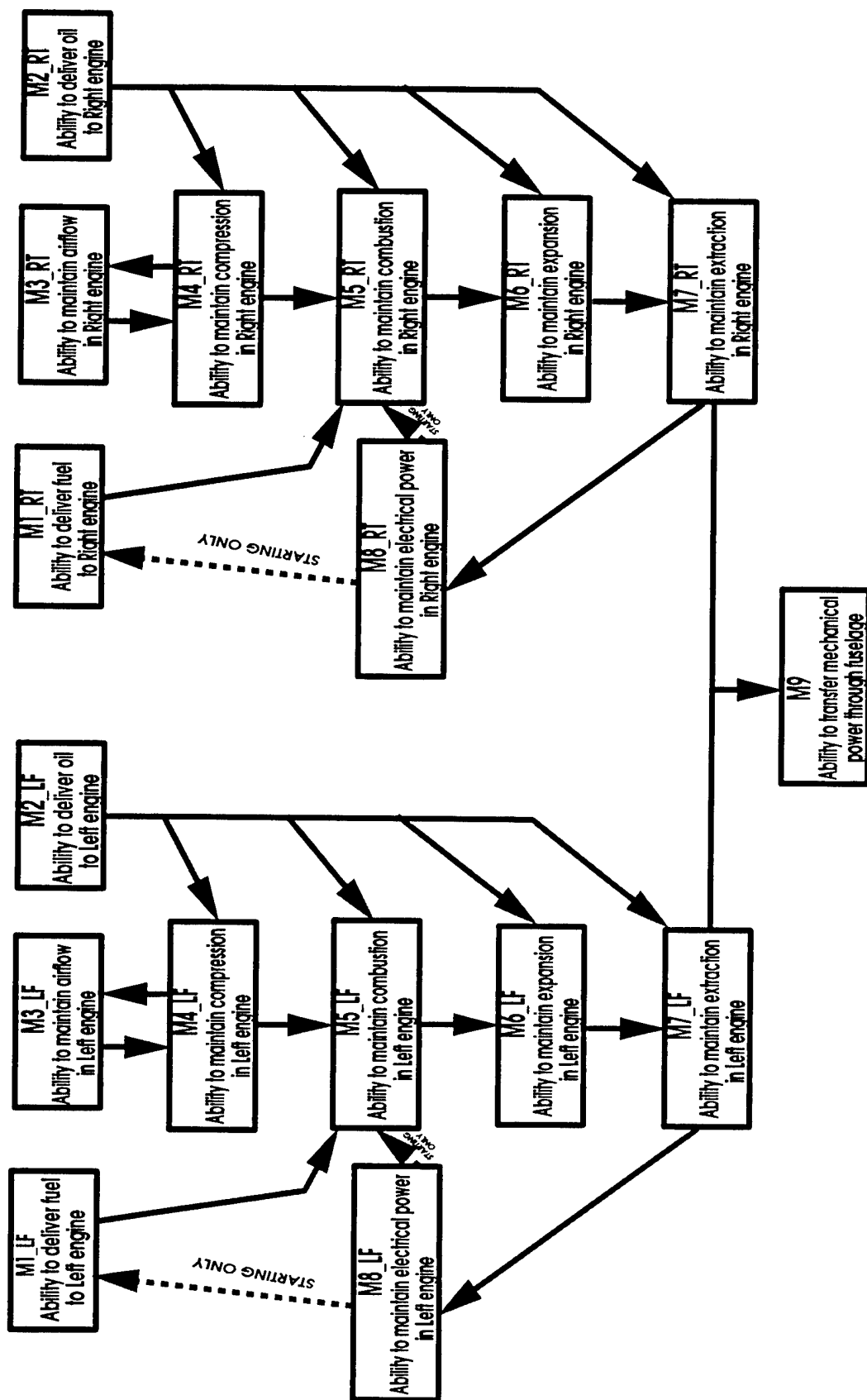**Figure 4. Powerplant/Power Distribution Capability Network for a Generic Military Helicopter.**

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lower the air pressure. This results in less air delivered to the compression chamber per time unit. Next, air is compressed in the left engine compression chamber, resulting in an increase in air pressure as well as an increased density/volume unit of air (**M4_LF**). Degradation to this capability would result in a decreased compression ratio (compressed air pressure/uncompressed air pressure). But this capability is also dependent on degradation to **M3_LF**. If less air per unit time enters the compression chamber, then less compressed air leaves the chamber per unit time.

Once the air flowing into the left engine has been compressed, it is then mixed with fuel in the combustion chamber and ignited by an electrical spark, resulting in a release of chemical energy (**M5_LF**). Degradation to this capability would result in a decreased release of chemical energy, perhaps as little as none at all. The amount of released combustive energy is dependent on fuel pressure (**M1_LF**), airflow (**M3_LF**) and compressed pressure (**M4_LF**), and the electrical spark (**M8_LF**). Within a turboshaft engine, mechanical power is generated by rotation of the power turbine, which is turned by the force released by the explosion in the combustion chamber (**M6_LF**). This process involves the application of the chemical energy released in **M5_LF** to perform useful work (measured in ft-lb) in **M6_LF**, such that the work involved in turning the turbine through one full rotation is

$$\text{Work} = \int_{\theta=0}^{\theta=2\pi} F_{combustion} * r_{turbine} \, d\theta = 2\pi \, (F_{combustion} * r_{turbine}) \, \text{ft} - \text{lb}, \qquad (12)$$

where $F_{combustion}$ = mechanical force released during combustion and $r_{turbine}$ = radius of the power turbine. This equation assumes that the combustive force is applied evenly through the turbine rotation.[*] The expansion capability within the left engine (**M6_LF**) is dependent on everything that **M5_LF** is dependent on, plus oil for lubrication (**M2_LF**).

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[*] In a real engine, not all of the chemical energy is converted to useful work; some of the energy is dissipated through heat. However, within the current example, heat loss is assumed to be a secondary effect and is thus not considered.

Within the left engine, the rotation of the power turbine imparts a mechanical rotational force to the shaft (**M7_LF**). The application of this rotational force over a period of time generates mechanical power, such that

$$\text{Power} = \frac{\text{Work}}{\text{Time}} = 2\pi \left(\frac{F_{combustion} * r_{turbine}}{t_{work}} \right) shp, \qquad (13)$$

where t_{work} = time interval in which the work is done and shaft horsepower. This equation also assumes that the work is done evenly over the time interval t_{work}. As previously mentioned, oil is pumped to the moving parts of the left engine in order to provide lubrication (**M2_LF**). Like fuel and air, a reduction in pumped oil/time unit will result in a lower oil pressure. This lower pressure could adversely affect the continued operation of the engine's moving parts, which could eventually lock up. Also, the rotating shaft powers an alternator, which generates electrical power (**M8_LF**). This electrical power is then required to run the fuel pump (**M1_LF**) and to provide an electrical spark for combustion within the left engine (**M5_LF**).

Referring to Figure 4, it is seen that networking of right engine (RT) capabilities is identical to that of left engine capabilities. Once left and right engine power have been independently generated, they are joined by the gear assembly, which combines and transfers mechanical power from the two engines to the main rotor of the helicopter (**M9**).

In the powerplant/power distribution capability network as illustrated in Figure 4, flow vectors that start at one capability and terminate at another capability form a chain, while a flow vector that maps back to its original or source capability forms a circuit. We can also point out source nodes in the network; these are capabilities where resources (fuel, air, oil, electricity) are introduced into the network flow process. In this case, the only independent source nodes (nodes with only an exit flow vector, so that the flow never returns to that node once it has left) are **M2_LF** and **M2_RT** (the sources of lubricating oil) and **M3_LF** and **M3_RT** (the sources of air).

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The processes within the powerplant/power distribution capability network can be specifically described by designing an algorithm that calculates normalized total engine power (**M9**) based on the operational states of the capabilities described previously, as well as the availability of required resources such as air and oil. Figure 5 lists such an algorithm, which is basically a set of conditional rules combining capability states with resource metrics (plus several other metrics such as **time_no_oil** and **LF/RT_air_pressure_sensor**) as listed in Tables 2, 3, and 4.

M3_LF = **LF_air_flow**/(15 lb/s)
M3_RT = **RT_air_flow**/(15 lb/s)

If **LF_air_pressure_sensor** = 1 and **M1_LF** = 1 and (**M2_LF** = 1 or (**M2_LF** = 0 and **time_no_oil** <30 min)) and **M3_LF** > 0 and **M4_LF** = 1 and **M5_LF** = 1 and **M6_LF** = 1, then
　　LF_power = **LF_air_flow** * (100 shp-s/lb)
　　M7_LF = **LF_power**/(1,500 shp)
Else
　　LF_power = 0
　　M7_LF = 0

If **RT_air_pressure_sensor** = 1 and **M1_RT** = 1 and (**M2_RT** = 1 or (**M2_RT** = 0 and **time_no_oil** < 30 min)) and **M3_RT** > 0 and **M4_RT** = 1 and **M5_RT** = 1 and **M6_RT** = 1, then
　　RT_power = **RT_air_flow** * (100 shp-s/lb)
　　M7_RT = **RT_power**/(1,500 shp)
Else
　　RT_power = 0
　　M7_RT = 0

engine_power = **LF_power** + **RT_power**
main_rotor_power = **engine_power** * 0.95
M9 = **main_rotor_power**/(2,850 shp)

Figure 5. Powerplant/Power Distribution Rulebase.

This rulebase is a set of logical relations and equations that model the flow of a resource (or multiple resources) within the network. In the current example, the overall capability of the powerplant/power distribution subsystem is addressed. The specific relations and equations are based on expert knowledge of generic helicopter turboshaft engine operation as relayed to the authors by Mr. Walter Thompson and Mr. William Keithley of the Air Systems Branch, Ballistic Vulnerability/Lethality Division (BVLD), SLAD, U.S. Army Research Laboratory (ARL) (Thompson and Keithley 1996). The rulebase assumes the aircraft has already been started.

Next, we describe each of the rules in the rulebase. First, the normalized airflow capabilities **M3_LF** and **M3_RT** are calculated based on a design optimal rate of 15 lb/s for each engine. Next, we define an operational condition for the left engine. Note that **M1_LF**, **M1_RT**, **M2_LF**, **M2_RT**, **M4_LF**, **M4_RT**, **M5_LF**, **M5_RT**, **M6_LF**, and **M6_RT** are modeled as binary metrics (capability/no capability), while **M8_LF** and **M8_RT** are not considered since we assume that the helicopter engines have already been started. So, in order for the left engine to function, capabilities **M1_LF** through **M6_LF** must be nonzero except for **M2_LF**, which can be zero provided that less than 30 min have passed since loss of that capability; in addition, the air pressure sensor must also be functional. If greater than 30 min, then the engines fail and the capability is lost. If this condition is met, then power generated in the left engine (**LF_power**) is directly proportional (by a factor of 100 shp-s/lb) to the mass rate of airflow (**LF_air_flow**). This kind of linear behavior is typical of turboshaft engines. Once **LF_power** has been calculated, the capability metric **M7_LF** is determined by normalizing left engine power to the design optimal value of 1,500 shp. If, on the other hand, the above operating condition is not met, then engine power is reduced to zero. The same rules are then applied to processes within the right engine to calculate engine power. Next, left and right engine power are summed to produce total engine power (**engine_power**). Finally, this last metric is multiplied by a transfer coefficient to determine power transferred to the main rotor (**main_rotor_power**), which itself is then normalized to a design optimal main rotor power of 2,850 shp to determine the capability metric **M9**.

The rulebase in Figure 5 can further be implemented as an analytical tool using the Modular Unix-Based Vulnerability Estimation Suite (MUVES) as developed by BVLD (Murray, Moss, and Coates 1994). Figure 6 lists the MUVES System Definition file as derived from the powerplant/power distribution rulebase. The calculated output metrics from the System Definition file are total engine power, main rotor power, and normalized main rotor power (**M9**).

M3_LF = LF_air_flow * 0.0667
M3_RT = RT_air_flow * 0.0667
oil_threshold = 30 - time_no_oil

LF_power = LF_air_pressure_sensor & M1_LF & (M2_LF | oil_threshold) & M3_LF & M4_LF & M5_LF & M6_LF
_if (LF_power, LF_air_flow * 100)
M7_LF = LF_power * 6.667E-4

RT_power = RT_air_pressure_sensor & M1_RT & (M2 | oil_threshold) & M3_RT & M4_RT & M5_RT & M6_RT
_if (RT_power, RT_air_flow * 100)
M7_RT = RT_power * 6.667E-4

engine_power = LF_power + RT_power
main_rotor_power = engine_power * 0.95
M9 = main_rotor_power * 3.509E-4

Figure 6. MUVES System Definition File as Derived From the Powerplant/Power Distribution Rulebase.

The above rulebase, which is now translated into a MUVES System Definition file, can be used in a ballistic-type analysis for a potential customer. For example, an analyst can use this rulebase to run numerous trials for a stochastic analysis. At first, it would allow the analyst to vary a number of airflow rates to determine the capability vector M1 through M9, as well as specific engine power output measured in shaft horsepower. Now assuming the worst-case scenario, where the oil supply is compromised, one can vary the airflow rates and calculate the results as a function of time. The

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caveat for the oil supply states an engine can run 30 min without any lubrication. The time factor is a consideration in the equation if, and only if, the oil supply is compromised. In addition to producing the capability vector M1 through M9 based upon various airflow rates into the left and right engines, one could calculate left and right engine power. From the previous information, an analyst can also provide the average left and right engine output power, respectively, as well as an average main rotor power. We might also consider the effect of certain environmental parameters at this level of capability granularity, such as the effect of helicopter flight altitude on **M3_LF** and **M3_RT**. For a generic air-breathing turboshaft engine, the rate of airflow (in pounds of air moved per second) changes from over 100 lb/s at ground level to less than 50 lb/s at 50,000 ft (Thompson and Keithley 1996). We can determine a maximum altitude where a minimum rate of airflow (as required for combustion) can be achieved. Thus, in this example, the altitude environmental parameter affects a source node in the network. Environmental parameters will be further discussed in the next section.

4.3 Mobility Response Surfaces. In the previous section, we described the process of mapping from "atomic" level capabilities (C^{MAX}) to a capability of lower granularity (C^{MAX-1}), specifically the powerplant/power distribution capability of a generic military helicopter. In this section, we describe the process of mapping from C^{MAX-1} to C^{MAX-2}, the next lower level of capability.

Referring to Figure 3, we see that there are three capabilities at the C^{MAX-1} level, each of which contributes to the formation of the mobility capability at the C^{MAX-2} level. In addition to the aforementioned powerplant/power distribution capability, there is also the control of aerodynamic surfaces (flight control) and structural integrity capabilities, each of which is functionally independent of the others but must "cooperate" with the other two capabilities in order for the helicopter to fly. The interaction of these three C^{MAX-1} - level capabilities is too complex to model with a simple set of linear rules as described in the previous section; what is required is an empirical model derived from helicopter performance data.

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Figures 7–9 illustrate the interaction of various capabilities using a response surface. This is a three-dimensional curve that shows the result of parametrically varying two variables, which may or may not be correlated. In the present example, these response surfaces illustrate the ability to cruise (an optimal level of 150 kn) as a function of main rotor power (an optimal level of 2,850 shp) and main rotor pitch control (an optimal total pitch variation of ±45°) (Figure 7), the ability to turn (normalized to an optimal turning radius of 20 ft) as a function of main rotor power and main rotor pitch control (Figure 8), and the ability to cruise as a function of ambient temperature and helicopter gross weight (Figure 9). Each of these response surfaces is actually a three-dimensional "slice" of the hyper-surface, relating mobility as a multielement vector "output" (of the form [ability to cruise, ability to ascend/descend, ability to hover, ability to turn]) of the multivariate function with "inputs" such as the capability metrics main rotor power, tail rotor power, and main rotor pitch control, as well as metrics such as helicopter gross weight, flight altitude, and ambient temperature. When a three-dimensional response surface is produced, those input variables not varied in the response function are fixed at specific values. For a multivariate function with m inputs and an n-tuple output vector, there are $0.5*n*m*(m-1)$ possible three-dimensional response surfaces.

The most important ingredient required to formulate a response surface is, of course, the system performance data. Although the data need not necessarily be empirical in nature, formulating an analytical performance model becomes more complex as m and n (as described in the previous paragraph) are increased. Although the data used to formulate the response surfaces pictured in Figures 7–9 are hypothetical in nature, they are modeled after the type of empirical helicopter performance data found in military technical/operator's manuals. The response surfaces shown here were generated by estimating a 2-tuple output vector for each of (4 points per input metric)$^{4 \text{ inputs}}$ = 256 input quartets and then fitting these points to a surface using a neural network algorithm (Wiggins, Borden, and Engquist 1992).[*] So, when combining a response surface with the previous process, and examining all pertinent parameters, to include time, one can generate a mobility vector. Considering multiple parameters will behoove the end-gamer, who has a direct connection with the

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[*] In order to actually generate the surfaces shown in Figures 8–10, the performance hyper-surface was constrained to four inputs (main rotor power, main rotor pitch control, helicopter gross weight, and ambient temperature) and two outputs (ability to cruise and ability to turn).
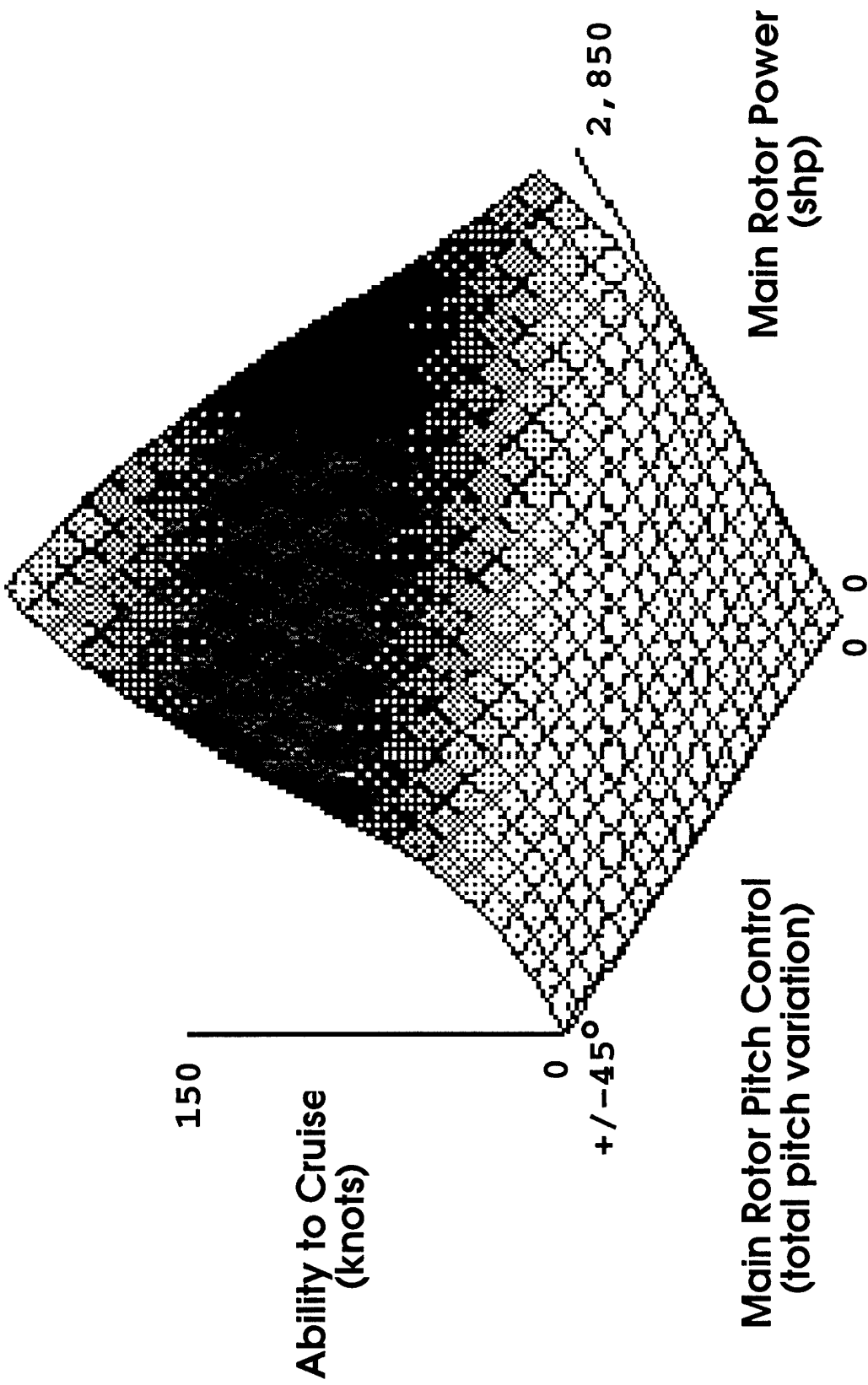
Ability to Cruise (knots)

150

0

Main Rotor Pitch Control (total pitch variation)

+/−45°

0

Main Rotor Power (shp)

2,850

0

0

Figure 7. Ability to Cruise as a Function of Main Rotor Pitch Control and Main Rotor Power.

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Ability to Turn
(turning radius in ft)

20

0

Main Rotor Pitch Control
(total pitch variation)

+/−45°

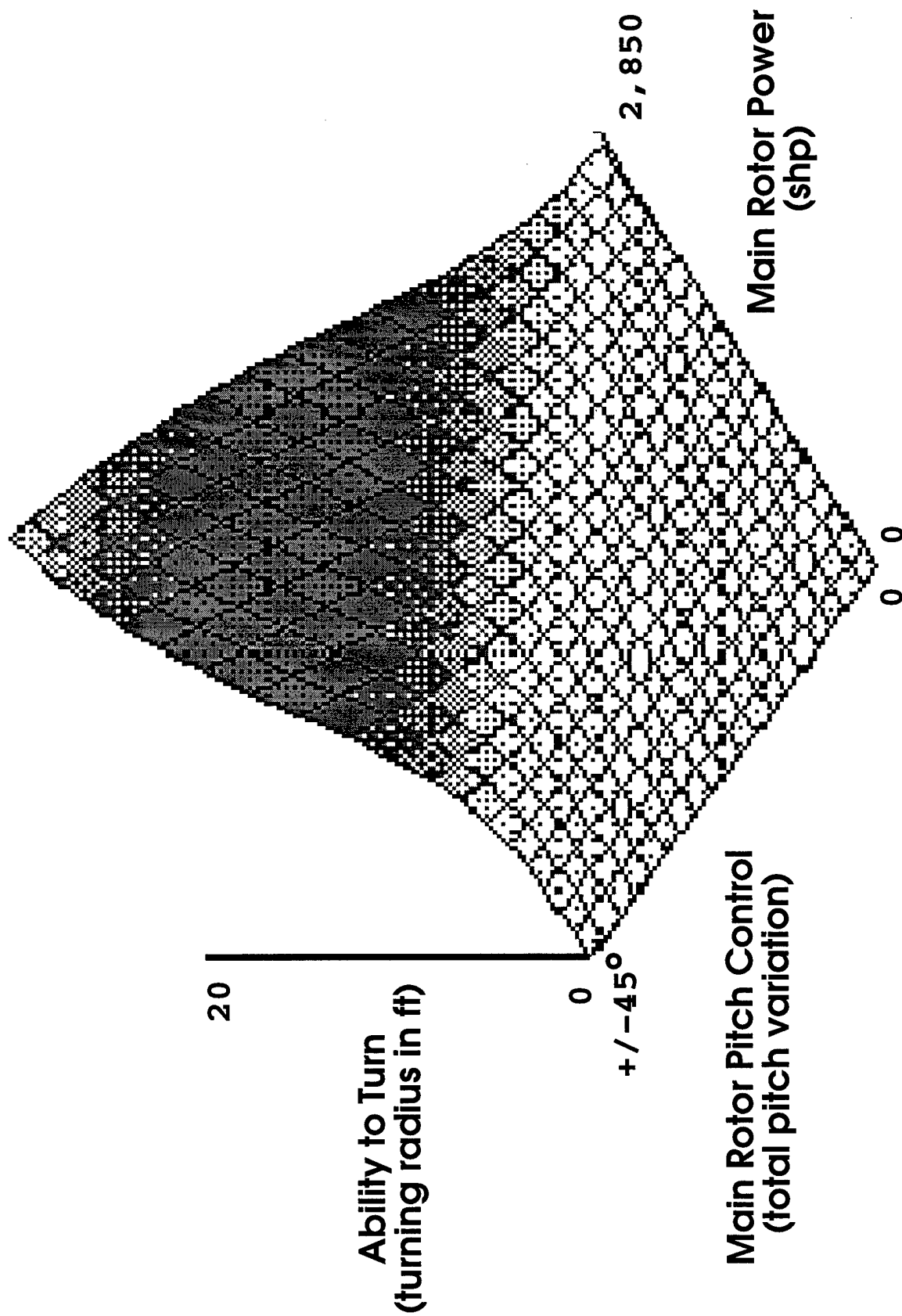0

Main Rotor Power
(shp)

2,850

0

0

Figure 8. Ability to Turn as a Function of Main Rotor Pitch Control and Main Rotor Power.
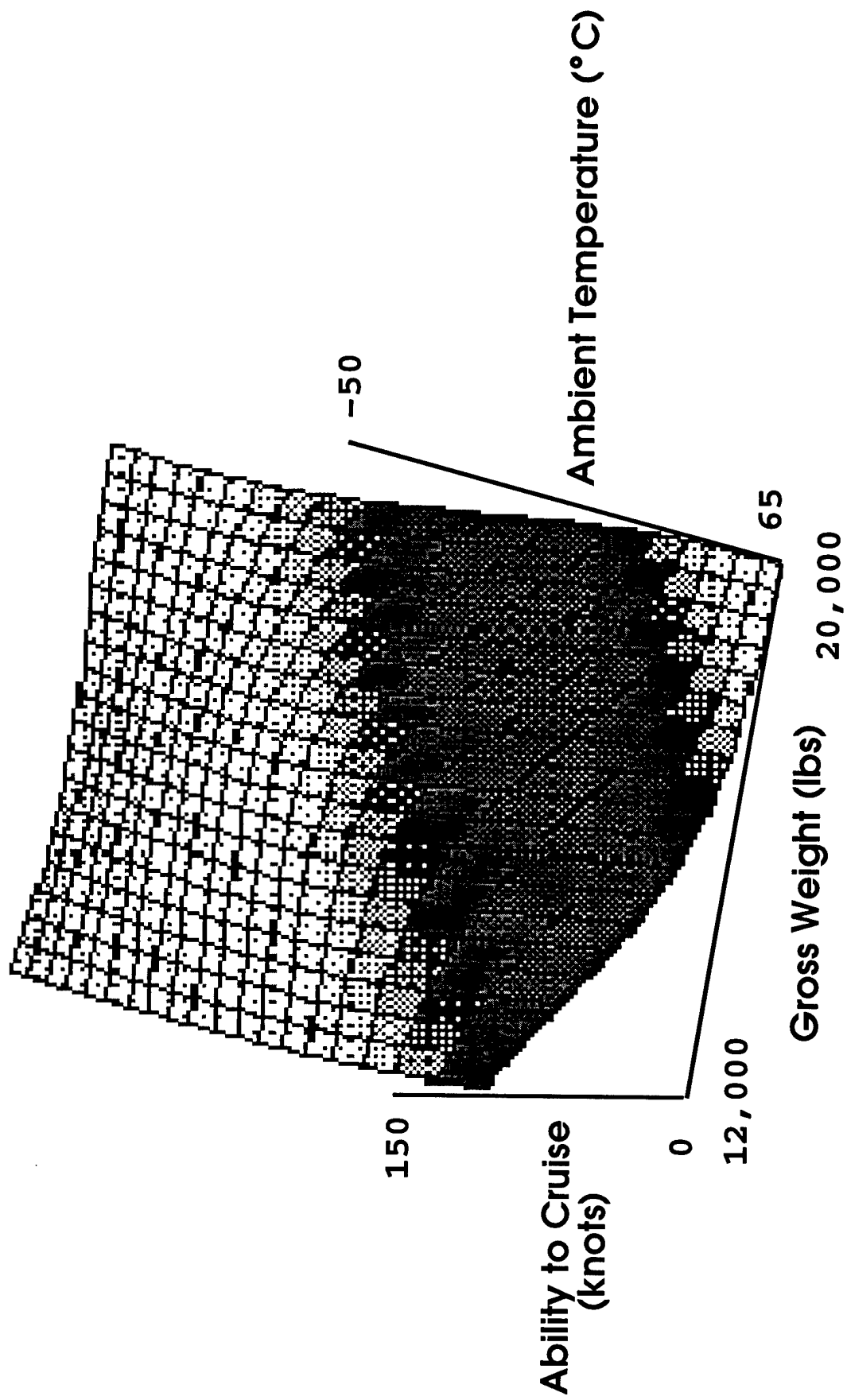
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Figure 9. Ability to Cruise as a Function of Helicopter Gross Weight and Ambient Temperature.

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soldier. In Figure 9, where the ability to cruise is normalized, one implies that one is flying at level pressure altitude at 150 kn. Assuming it to be linear, one can interpret that halfway down the axis would imply flying at a level pressure at 75 kn.

5. Conclusions

In this report, we have illustrated, through several examples, how capability metrics may be quantified by relating the resultant capability levels to quantified Level 2 metrics. We have also shown how capability metrics may be defined at different levels of granularity and the process of mapping from higher to lower capability granularities using both capability networks and response surfaces. With these new tools, an analyst can provide specific performance metrics to the customer. To enhance the current methodology (Roach 1996), one can see that capability vectors and response surfaces can provide performance characteristics of the system or subsystem to various threats from an engineering or mission point of view.

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13. ABSTRACT *(Maximum 200 words)*

The analysis process through the years has progressed to see the evolution of measurable and observable metrics. Trying to enhance the process is an ongoing endeavor and pursuit. Recently, the work has been focused on tailoring system analysis output metrics for input into end-game simulations. The concepts introduced in this report will attempt to address this issue; these concepts include (1) the quantification of capability vectors, (2) capability granularity, and (3) capability networks.

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