HUMAN VISUAL PERFORMANCE MODELING

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ABSTRACT

Tactical weapon systems frequently depend on electro-optical sensors for engaging targets. Many of these electro-optical sensors utilize a man-in-the-loop. In such systems, the human eye is the critical *processing element and is therefore the fundamental determiner of the sensor's effectiveness. This is* true whether the sensor is the unaided eye (with or without magnification optics) or the eye in concert with devices which convert energy into the visible spectrum.

Simulations which intend to assess the effectiveness of proposed and existing sensors require accurate models of human visual performance. Unfortunately, human vision simulation models are generally immature, poorly understood, and more theoretical than practical. The paper presents a method for modeling human vision which represents a synthesis of existing methodologies for characterizing human visual performance. The method involves an approach which is useful to non-specialists, and will address all electro-optical sensors which utilize a man-in-the-loop. The paper reviews the tasks associated with engaging targets, by using a generic tactical weapon system to characterize the sequence of events to be modeled. Finally, the paper discusses the implementation of the model and its application in various simulation environments.

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INTRODUCTION

The end of the cold war has spelled the end of intensive development in strategic weapon systems -- this has not been the case for tactical systems. While it is unlikely that the country will face the kind of all-out struggle for survival that requires strategic systems, it is very likely that we will face a series of smaller conflicts. Indeed, the debate over the defense budget is quickly becoming a game of "how many Desert Storms at one time" should we be capable of fighting. Such conflicts may be less intense for the nation at large, but are just as deadly for the soldier in the field. The army of tomorrow requires lethal and survivable tactical weapon systems.

What do we mean by a *tactical weapon system*? Of course, a system is a interrelated set of components working together to achieve a common purpose. In this case, the purpose is the destruction of enemy assets, or the defense of friendly assets. The components of the weapon system include sensors, projectiles, platforms, propulsion devices, and so forth. Tactics concern the maneuver and arrangement of individual weapons systems, whereas strategy is concerned with force assignment. Thus, a tactical weapon system is one whose individual activities are significant to the outcome of the battle. Examples of such systems include air defense vehicles, helicopters, and assault vehicles.

A common feature of a tactical weapon system is the utilization of the operator as the primary sensor. This design approach is driven by two causes: (1) the cost of automated target recognition capability, and (2) the inherent desire for a man to control the machine. The eyes of the operator, whether unaided, with direct view optics, or with an imaging device, define the capability of the system to find other weapon systems and classify them. The operator's eyes can be an integral part of guiding the weapon to the target. As a sensor, the human operator must perform several critical tasks. If these tasks are performed in an appropriate and timely manner, the operator will bring the weapon system to bear on the threat and engage it successfully.

Simulation is a valuable tool for the design of lethal and survivable weapon systems. The bulk of investment in simulation technology has been for strategic systems, which are (in a way) easier to model. Strategic systems by definition involve large numbers, vast distances, and tremendous effects. Therefore, models of *macro-effects* (i.e., stochastic models) are suitable for simulation of battles involving strategic systems. Tactical systems, on the other hand, are much more intimate, depending on *micro-effects*. Stochastic models do not adequately model tactical battles because the number of units involved is much smaller and the outcome depends much more on individual performance. One such micro-effect is the quality of the operator's vision.

Therefore, the design of training for tactical weapon systems is more difficult than similar devices for strategic weapon systems. This difficulty has led to the use of networked simulators, such as SIMNET. Such systems exercise the most important effect on the tactical battle, namely the interaction between weapon systems and their crews (strategic systems tend to be more autonomous). Advances in networks, such as the Advanced Distributed Simulation Technology, are providing the ability for system designers to explore system concepts before implementation of full scale development efforts. However, when a trained crew and fully developed hardware are not available, the need for estimation of human visual performance can be readily seen.

Simulating systems with human vision as an integral part of the engagement process is a requirement for system design and some training environments, and a modeling challenge. Without proper regard for the human visual performance, any conclusions derived from the simulation are highly questionable. Available simulation tools do not possess the fidelity or capability to adequately address systems of this type.

TARGET ENGAGEMENT DESCRIPTION

We are interested in modeling the modes and states of the weapon system in which the visual performance of the operator plays a critical role. At what point is the operator's visual performance important? A weapon system exists within a command echelon. At any given time, the command echelon can order the weapon system into a specific *mode* (maintenance, training, deployment, ...). Of the modes which a tactical weapon system might assume, the target engagement mode is the most important. Obviously, a weapon system exists to engage targets, and all the other modes simply support this mode. Engagement is also the mode in which the visual performance of the operator plays a central role in determining mission success. Therefore, the primary requirement for a model of visual performance is that it adequately represents the visual tasks performed in engagement mode. We refer to the performance of a visual task as a *visual process*. The rest of this discussion neglects the remaining weapon system modes.

How is the engagement mode defined? Figure 1 is the transition diagram for the target engagement process. We immediately notice that some visual task defines the transition between states (except for entry and exit into engagement mode, which are by command). Also, notice that engagement is generally a *cyclic* process, moving orderly between search, track, and fight. Each of these states has an objective and set of functions which relate directly to the purpose of the target engage mode. Some of these states have equivalent states in other modes (e.g., the track state within the test mode); however, the objective and functions of a state are defined by its host mode. The following discussion describes the command to engage, the states within engage, and the visual processes on which the state transitions depend.

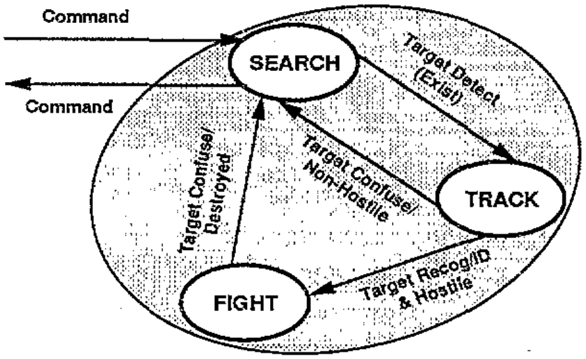

Figure 1
Engagement Mode State Transition Diagram

The decision of the command echelon to order the tactical weapon system into engage mode includes a deployment location/time, an assessment of the threat to be faced, an assigned area of responsibility, and a set of rules of engagement for the present tactical situation. Within the context of our discussion, the significant portions of the command are the area of responsibility and the rules of engagement.

The weapon system's area of responsibility defines the *field of regard* for the visual processes. The field of regard is an angular sector within which the weapon system may engage targets, given that the criteria within the rules of engagement are met. Note that field of regard is a geometric space without regard for the intervening terrain, vegetation, atmosphere, or cultural features. The field of view is the particular portion within the field of regard that is perceived by the sensor at any given time. Thus, a target within the field of regard may be occluded from the sensor's field of view by a tree or a hill.

The rules of engagement may be summarized as a choice between *weapons free* and *weapons tight*. Weapons free indicates that friendly units are not expected in the field of regard. This situation requires the weapon system to apply the *recognize* visual process in order to transition from track to fight. Weapons tight indicates that friendly units may be present in the field of regard. This situation requires that the weapon system make a positive *identification* in order to transition from track to fight. Note again that visual processes provide a scheme to implement these rules of engagement in a simulation.

The *search* state models the process of sweeping the assigned field of regard with a sensor in order to find a target. Generally, the field of view of the sensor will not completely encompass the field of regard, as shown in Figure 2. In such cases, the sensor(s) must make a series of *placements* in time over the field of regard in order to locate the target. The placements, defined in terms of azimuth and elevation, may be made in a disciplined or a haphazard fashion. The objective of the search state is to locate targets within its field of regard. The sensor system locates targets by detecting their presence within its field of view. The weapon system transitions out of search when it decides to track a detected target, or the command echelon orders it to exit from the engagement mode.

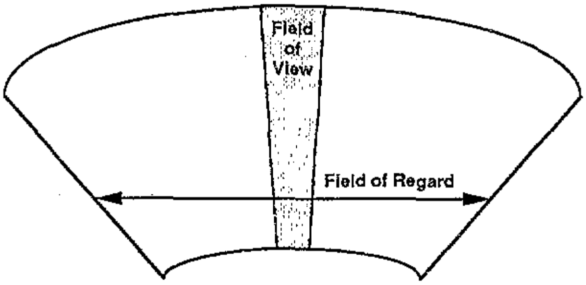

Figure 2
Field of Regard versus Field of View

The *track* state models the process of maintaining the target in the field of view after it has been detected. The target is kept in the field of view by matching the target's motion with the sensor using a manual or automatic slewing process. The objective of the track state is to determine whether or not the target is hostile. The weapon system transitions out of track when it can determine a target's hostility according to the rules of engagement. If the system determines the target is hostile, it may transition into the fight state; if non-hostile, it may transition to the search state to seek new targets. The weapon system will also transition out of the track state to the search state, if the target track is confused.

The *fight* state models the process of employing the weapon system's ordnance to destroy the target. Generally, the weapon system will continue to utilize the track function in this state, either to guide a weapon, or to determine the weapon's effectiveness. While fighting, the weapon system may change its determination of the target's hostility. In addition, it is possible that the weapon system might be confused while fighting, just as in the track state. Either event would cause the weapon system to transition out of the fight state and back to search.

While the states of the engagement process apply to every tactical weapon system, the details of a state model depend on the specifics of a given weapon system. Internal details such as the number and assignment of sensors, the number of crew members, the number of simultaneous tasks permitted, etc., vary widely between systems. This variation between systems greatly complicates the task of creating a generic state model. However, the focus of our interest is simulating human visual performance. In the case of a weapon system, we can simulate this performance by modeling the process by which the operator completes the necessary visual tasks. While the internal details of the state models do not depend on visual processes, the transitions between these states depend on visual processes. Therefore, visual process models are the focus of this paper. The following discussion introduces the four visual process models required for system simulation: detection, recognition, identification, and confusion.

Detection means that the presence or absence of a target may be discerned by the observer. The presence of a target may be indicated by (1) the target's motion relative to the scene, or (2) the target's appearance disrupting the scene. Regardless of the cue, detection simply means "something is there." Detection is necessarily a time dependent process. Each placement of the sensor system occurs for a brief period of time, during which the weapon system may or may not detect any targets present in the current field of view. If the weapon system detects multiple targets, it must select one (or perhaps a closely packed group) to pursue.

Recognition means that the observer has sufficient resolution to enable him to determine the class of the target, e.g. helicopter or fixed wing aircraft. Recognition is possible when just a few features of the target are visible, such as propulsion devices, turrets, etc. Like detection, recognition is a time dependent process. The more time the sensor has to observe the target, the more likely that recognition will occur. The recognition process may be aborted by confusion in the scene. The recognition process is used to determine the hostility of a target under certain rules of engagement.

Identification means that the observer has sufficient detail to be able to determine the particular model of the target, e.g., UH-1, UH-60, Mi-24, etc. Identification is possible when specific details about the target are visible, such as the location of weapons, hatches, etc. Identification is also a time dependent process. The more time the sensor has to observe the target, the more likely it is that identification will occur. The identification process may be aborted by confusion in the scene. The identification process is used to determine the hostility of a target under certain rules of engagement.

Confusion about the target may result from two causes: (1) inability to retain track or (2) multiple targets entering the scene. The weapon system is unable to track the target when it cannot keep the target within the sensor's field of view. This may be a mechanical failure of the sensor system (e.g., a slow pivot), or a result of sensor ineffectiveness (e.g., an intervening cloud). The fact that the track function's field of view is often smaller than the search function's field of view is a further complication of the visual tasks. If multiple targets enter the field of view, the weapon system must decide which target to track. This decision is often based on a priority list determined by the rules of engagement -- a problem outside of the purview of visual performance.

REQUIREMENTS

As stated, the operator's visual performance drives the engagement process for a tactical weapon system. What characteristics of the visual processes must find their way into vision models for a tactical weapon system simulation? Realistic visual process models must address: (1) appropriate physiological realities, (2) time dependencies, (3) sensors other than the human eye, (4) multiple targets, and (5) emergence of multiple distinct targets from one target "clump". An example of physiological effects is the eye's response to contrast. Time dependency is important because it reflects the fact that the eye is an integrator of the scene it perceives. Other electro-optical sensors, such as direct view optics, night vision goggles, imaging infrared systems, etc., fundamentally depend on the eye's performance. Clearly, tactical scenarios will include scenes with multiple targets, which the model must consider. A sensor may not be able to differentiate between multiple targets in close proximity to one another. In such cases, the sensor may perceive the targets as a single large target, or *clump*, which again must be considered.

The visual process models depend on characterizations of the sensor, the environment, and the targets. The characterization of the sensor will describe resolution performance, field of view, and operating wavelength. The characterization of the environment will describe the effects of intervening atmosphere, terrain, vegetation, and cultural features. The characterization of the targets will describe, with respect to the sensor, relative position, relative orientation, and signature. In addition to the above external characterizations, the visual process models must retain internal state data. With these details, the models can simulate the performance of the sensor in a given tactical engagement.

What kind of model will account for these requirements in a straightforward and realistic manner? One answer might be to build a detailed simulation of the eye including individual rods and cones, communication along the optic nerve, and information processing within the cerebral cortex. While a simulation of this type might be of interest to a physiologist, it is too complex for scenarios of interest to tactical weapon systems analysts. Another solution might be to utilize laboratory and field measurements of processes involving the eye. While these studies are very useful, the biggest drawback to their use is the lack of sufficient generality. Experiments of this type are difficult to perform, and are necessarily limited in their scope. The best answer for modeling human visual performance would appear to lie between these two extremes. Fortunately, several methods for modeling human visual performance do exist.

The first method, developed by the British, uses a visual lobe approach to model detection [1]. The visual lobe is defined as the angle from the foveal axis at which the human eye can just detect a target. This method does not support modeling sensors other than the human eye, and does not lend itself to modeling of visual processes other than detection.

The second method, developed by H. H. Bailey at the Rand Corporation, uses a threshold contrast approach to model recognition [2]. The threshold contrast is a function of the target contrast and size, the number of resolution cells across the target, the required search area, the available search time, the scene clutter, and the signal-to-noise ratio. This method includes time as an independent variable, and can be used for sensors other than the human eye, but does not lend itself to modeling of visual processes other than recognition.

The final method, developed at the Center for Night Vision and Electro-Optics (CNVEO), uses the spatial resolution of the sensor to compute the probability of detection, recognition and identification [3,4,5]. The connection between the spatial resolution of the sensor and the probabilities is the Johnson criteria [6]. The Johnson criteria is an empirically derived relationship which relates the ***resolved number of cycles across the target*** *to the probability of accomplishing a visual* task. The resolved number of cycles across the target is related to the spatial frequency of the smallest equivalent bar pattern that can be resolved by the sensor. The CNVEO calculations depend on (1) the number of resolvable cycles across the target, (2) the number of cycles necessary to achieve a particular visual task, and (3) a qualitative measure of clutter effects. It also models the time dependencies of the visual processes. This method can model sensors in addition to the human eye and lends itself for modeling all of the visual processes of interest.

Of these three methods, the CNVEO approach spans our minimum requirements, primarily because it presents a single methodology for computation of probabilities of detection, recognition and identification. This method has been adopted by the U.S. Army, as well as several other allied countries. It can support simulation of multiple targets. However, the method does not fully support simulation of dynamic engagements. As originally envisioned, the CNVEO method modeled static scenes, i.e., both the observer and the target are stationary for the duration of the process.

EXTENDED METHOD

We begin by reviewing the CNVEO method. Figure 3 illustrates the process flow for the method. The coefficients necessary to compute the transmittance are found in handbooks such as the *Quantitative Description of Obscuration Factors for Electro-Optical and Millimeter Wave Systems* [7]. Further, this handbook contains a simplified set of equations for computation of apparent contrast and apparent temperature differential. We review the remaining steps in the CNVEO method in some detail to support our later extensions.

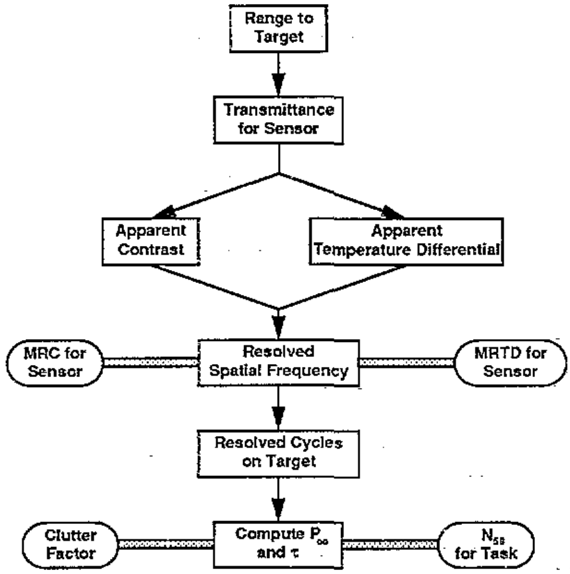

Figure 3
Process Flow Diagram for CNVEO Method

The resolved spatial frequency is computed by using the computed apparent contrast (for a visible sensor) or the apparent temperature differential (for infrared systems). Figure 4 illustrates the minimum resolvable contrast (MRC) for a human eye in daylight conditions [5]. The MRC or the minimum resolvable temperature differential

(MRTD) curve defines the relationship between contrast/temperature differential and resolved spatial frequency. The number of cycles resolved across the target, N_t, is computed as the product of the resolved spatial frequency and the angular subtense of the target.

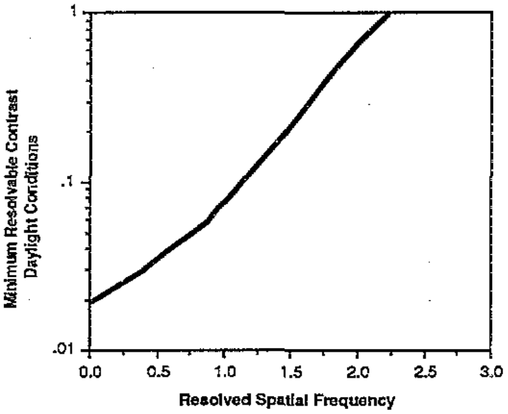

Figure 4
Human Eye Performance Characterization (Reference 5)

Recall that the Johnson criteria defines an empirical measure of the number of cycles necessary to achieve a visual task. This empirical measurement is referred to as N_{50}, defined to be the number of cycles necessary for a 50% probability of accomplishing the visual task. The value for N_{50} depends on the task to be accomplished and a qualitative measure of the amount of clutter present in the scene. References 5 and 7 contain additional information about computation of appropriate values for N_{50}.

Given N_t and N_{50}, we can determine the value of P_∞, which is the probability of visual task accomplishment given an infinite amount of time to stare at the scene. Let $N_{ratio} = N_t / N_{50}$. Then, P_∞ may be defined as:

$$P_\infty = \frac{(N_{ratio})^E}{[1 + (N_{ratio})^E]} \qquad (4.1)$$

where $E = 2.7 + 0.7\ (N_{ratio})$.

The next step is to use P_∞ to determine the mean time to accomplish the required task or τ. This is given by:

$$\tau = \begin{cases} 3.4 / P_\infty & N_{ratio} \leq 1.84 \\ 6.8 / N_{ratio} & N_{ratio} > 1.84 \end{cases} \qquad (4.2)$$

With all the terms in the equation defined, the expression for the probability of task accomplishment as a function of time for detecting a single target within the field of view is:

$$P(t) = P_\infty [\ 1 - exp(\ -t/\ \tau)] \qquad (4.3)$$

As discussed previously, the CNVEO model was developed for static scenes. However, the target engagement process for a tactical weapon system is anything but static. We must be able to model the process of moving target/moving observer target acquisition if we are to maintain any sort of fidelity in our model. How can we modify the CNVEO model to account for this? If we assume that for a very small time, say Δt, that the scene is static, then we should be able to use the CNVEO equations for that time period. Therefore, we will replace equation 4.3 with the following:

$$P_i(t) = P_{\infty_i} [\ 1 - exp(\ -\Delta t_i/\ \tau_i)] \qquad (4.4)$$

where the variables subscripted with i refer to the i^{th} time interval.

Equation 4.4 is the instantaneous probability of task accomplishment over the time period Δt. We can then derive an equation for the cumulative probability of task accomplishment over m time periods. The probability that the task will not be accomplished in Δt is $1 - P_i(t)$. Therefore, if we examine the probability of accomplishing the task over m identical time periods, the cumulative probability, $P_c(t)$, is given by:

$$P_c(t) = 1 - \prod_{i=1}^{m} [1 - P_i(t)] \qquad (4.5)$$

where, $t = m * \Delta t$.

Thus, we have extended the CNVEO model to account for dynamic scenes. The probability of accomplishing the visual task at hand will accumulate correctly even when the target is not in the current field of view. The cumulative probability functions are assumed to have perfect memory, i.e., no loss of information will occur over time, with the exception of target confusion. If a target is not present in the field of view, the instantaneous probability will be zero, and the cumulative probability function will remain constant until a target is present.

The detection of multiple targets with the CNVEO model poses a challenge. Some work has been done [8] to extend the CNVEO methodology to cases where multiple targets in static scenes are encountered. However, these extensions are not relevant to our dynamic scene requirements. We will use the single target model for each target present within the field of view and keep track of the probability of task accomplishment for each of these. In this manner, we can allow for targets to leave the field of view and enter the field of view without upsetting the probability calculations.

Another required extension is "target clumping." If we have two targets that are close to one another, a particular sensor may not have sufficient resolution to enable the observer to distinguish one from the other. Should this situation occur, we will artificially construct a single target. We will treat this *composite* target as if it were a single target. However, we will prohibit recognition or identification of the composite (he should be able to distinguish between the targets before "recognizing" the composite). When the observer can distinguish between targets in a clump, the composite target is marked invalid and multiple targets are reported. This can be computed by knowing the number of cycles resolved across the target's horizontal dimension. The observer can resolve the presence of two targets when the width of a single cycle is less than or equal to the horizontal separation of the targets.

While the foregoing fulfills the needs of the detection, recognition, and identification, it does not yet support confusion. Therefore, we address confusion as a set of groundrules. One cause of target *confusion* is multiple targets entering the field of view while the track function is being utilized. The other cause is when a tracked target leaves the field of view. When the visual model determines confusion exists, the visual process will report confusion, and the weapon system model will implement the impact of confusion on the sensor system activities. In addition, the visual model will reset the cumulative probability of recognition and identification to zero when confusion occurs.

APPLICATIONS

There are many simulation situations which require modeling of human visual performance. There are three applications within our organization which utilize the described method to model visual processes: (1) an analytical one on one engagement simulation, (2) a probabilistic small force simulation, and (3) a stand alone analysis tool. In the stand alone version, the model supports familiarization training for unusual or foreign sensors. Figure 5 illustrates the top level structure of the analytical simulation. The environment manager within the analytical simulation utilizes the visual process model to simulate the ability of moving models (such as weapon platforms and projectiles) to "see" targets.

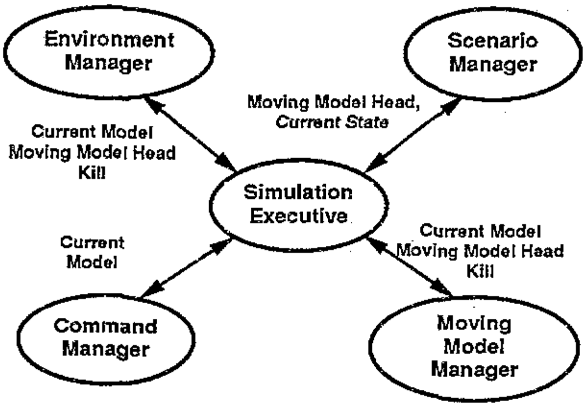

Figure 5
Analytical Simulation Context Diagram

The probabilistic simulation does not directly utilize the visual process model in the course of execution. However, this simulation does depend on a set of input probabilities, including the likelihood of finding hostile targets in a scenario. The probabilistic simulation needs such probabilities of discovery from two perspectives: (1) the probability of discovery at specific ranges given infinite observation time, and (2) the probability of discovery at specific simulation times given infinite observation time. The second perspective is used to support simulation of time evolving obscurants, such as smoke clouds.

A third application of the visual process model is as a stand-alone analysis tool for preliminary investigations. In the stand-alone configuration, we can set up a specific target/observer geometry and compute the probability of completing any of the visual tasks.

The implementation of these models in software is non-trivial. We desire an approach which maximizes the flexibility and reusability of the developed software. Therefore, we used an object-oriented design approach, by which we mean that the design attempts to apply the principles of abstraction, encapsulation, and inheritance. *Abstraction* calls for a design that creates a hierarchy of detail about the object. *Encapsulation* calls for a design in which the internals of an object exhibit tight cohesion, and the intra-object relationships are loosely coupled. *Inheritance* calls for a design which recognizes that nothing is truly a "new" start, therefore a design should build and expand on previous efforts. An object-oriented design begins with the selection of system components to be designated objects. This process continues, breaking down system objects into sub-objects and refining object definitions until the system is completely elaborated.

Figure 6 illustrates the design objects and the interactions between them. The first tier of the design defines the top level objects: platform, command, and visual environment. The platform object encapsulates the details of the weapon system specific models. The command object encapsulates the details of the command echelon supporting the weapon system. The environment object encapsulates the details of the environment including the visual process model.

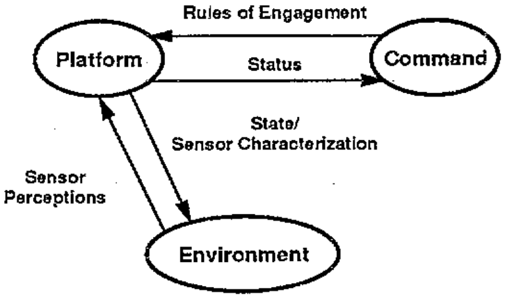

Figure 6
Top Level Objects

Clearly, the dichotomy between the top level objects parallels that between the state and transitions of the engagement process. The states of the engagement process are encapsulated by the command and moving model objects. The internal details of the command and moving model objects do not depend on visual processes, but abstract various system specific information and functions. On the other hand, the transitions between states depend on the various visual process models, which are encapsulated within the environment object. Therefore, our interest for this paper focuses on the breakdown of the environment object.

Figure 7 illustrates the breakdown of the visual environment sub-object within the environment object. The other portions of environment, which contribute environmental details such as terrain, culture, etc., do not involve visual processes. The visual processes are encapsulated within the visual environment object, which expects inputs characterizing the sensor, such as: sensor state, field of view, MRC, etc. In addition, it expects inputs characterizing the environment, such as: terrain, culture, weather, and obscurants. The visual environment object must have access to a global view of all targets within the scenario. There are three sub-objects within the visual environment object. The field of view object resolves the field of view against the environment and target location information, to produce a potential target list. The electro-optical (EO) sensor object computes the cumulative probabilities for the active visual processes: detection, recognition, or identification. In addition, the EO sensor object clumps targets together, if they are close enough that the sensor can not distinguish between individual entities. The vision

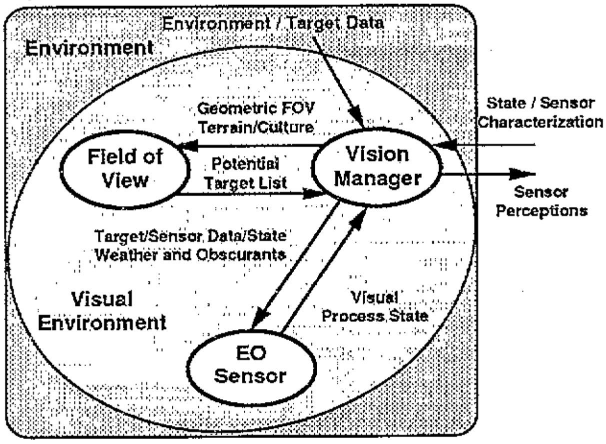

Figure 7
Second Tier Objects: Visual Environment

manager object invokes the other sub-objects with the appropriate values for the scenario. It records the cumulative probabilities for each visual task for each sensor, and determines if the relevant threshold has been crossed. Finally, it evaluates the possibility of sensor confusion. For each sensor, the vision manager object will report out the sensor's perceptions.

CONCLUDING REMARKS

In this era of declining defense budgets, many companies are finding that acquiring and maintaining a technological advantage over their competition is not necessarily a guarantee of success. Success requires a marriage between technology and operations, both of which must evolve with the user requirements. The evolution of a realistic operational concept for a weapon system is both an analysis and design function. Simulation is an ideal tool for conducting the functional trade-offs between potential designs.

Our organization deals with the simulation of tactical weapon systems for the purposes of training, scenario evaluation, and requirements development. The kinds of scenarios of interest to us are assaults by tactical air units (rotary and fixed wing) against assets defended by tactical air defense units. The capability of the air-to-ground unit to acquire a target against various terrain configurations is critical for its mission success. The capability of the ground-to-air unit to pick out its target against the sky and terrain is almost as tough, and just as important. Who sees who first (and with what quality) is typically the primary measure of effectiveness for tactical engagements. Of course, we would prefer to use actual human vision in the simulation, but this is cost and time prohibitive. Even when the simulations are being used for training (i.e., with a man in the loop), men are not available to staff the opposing force. Therefore, the ability to model human visual performance is critical for our simulations to achieve their purpose.

Tactical weapon systems typically utilize a human as a primary sensor as well as the sensor fusion point. Therefore, the model of the operator is central to successful simulation of tactical weapon systems. The visual process method presented herein supports simulation of the various sensor system which utilize the human eye as a primary sensor component. It provides a flexible and general assistance for tactical weapon system simulation. We intend to continue the implementation of our method towards the goal of providing robust simulation of human interaction with sensors in tactical weapon systems. Further, we intend that the method be extended to provide the ability to simulate the performance of a tactical sensor in a training environment.

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