

TRADEOFFS IN THE CONFIGURATION OF COMPUTER IMAGE GENERATION SYSTEMS

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ABSTRACT

This paper analyzes the tradeoffs involved in Computer Image Generation (CIG) system configuration and their implications for the developers of training systems. Most CIG visual system products have important interrelationships between system parameters and performance. An understanding of these interrelationships and their application to training systems will provide the basis for tradeoff decisions. These tradeoffs will permit proper alignment of CIG system parameters to training application requirements, resulting in cost reductions and improvements in training effectiveness.

This paper includes a comprehensive discussion of the important CIG parameter and performance interrelationships. For example, it discusses how viewing range, field of view angles, polygon throughput, and database density relate to provide different levels of image effectiveness. This paper also discusses how optical magnification, screen resolution, and antialiasing combine to influence the user's ability to detect, identify and recognize objects in a scene.

In the past, high fidelity CIG's have been used for aircraft out the window (OTW) views for training military and commercial pilots. The simulator "crew" had a common view and common task. Today, systems simulate tanks and helicopters training multiple "crew" members, each having different views of the scene and different tasks. The visual simulation must support multiple OTW views, periscopes, magnified optical sights, thermal and TV sensors within the same vehicle. In this paper, visual system requirements of different training applications such as ground vehicle driving, and precision gunnery are reviewed.

The paper will conclude with examples of how to use this analysis of interrelationships and tradeoffs to reduce CIG costs, and to prevent underachievement of training objectives or excessive specification for visual performance.

INTRODUCTION

Computer Image Generation (CIG) systems are very complex products which are difficult for the non-expert to evaluate. One reason CIG products are difficult to evaluate is that their various parameters are often interrelated in an adverse way, so that increases in one parameter lead to reductions in another. In this paper I discuss the various parameters of CIG systems and the tradeoffs between them. Later in this paper I discuss the relationship between these parameters and specific training applications.

The ability of the human to interpret the computed visual scene in order to perform tasks is the real measure of CIG effectiveness. These requirements are discussed with specific tradeoffs to improve image complexity and fidelity. Understanding of such tradeoffs will permit even the non-expert to properly match the specification of CIG system parameters to specific training application requirements, resulting in cost reductions and improvements in training effectiveness. [1]

ANALYSIS OF PERFORMANCE TRADEOFFS IN CIG SYSTEMS

Performance parameter relationships will vary from CIG system to system due to the different computer architectures and graphics algorithms used. Many relationships have direct tradeoffs with either one or more parameters, and some are more indirect. Tradeoffs are caused by the interrelationships of the processing elements that make up a CIG computer. Figure 1 shows many CIG parameters that are related and have tradeoffs.

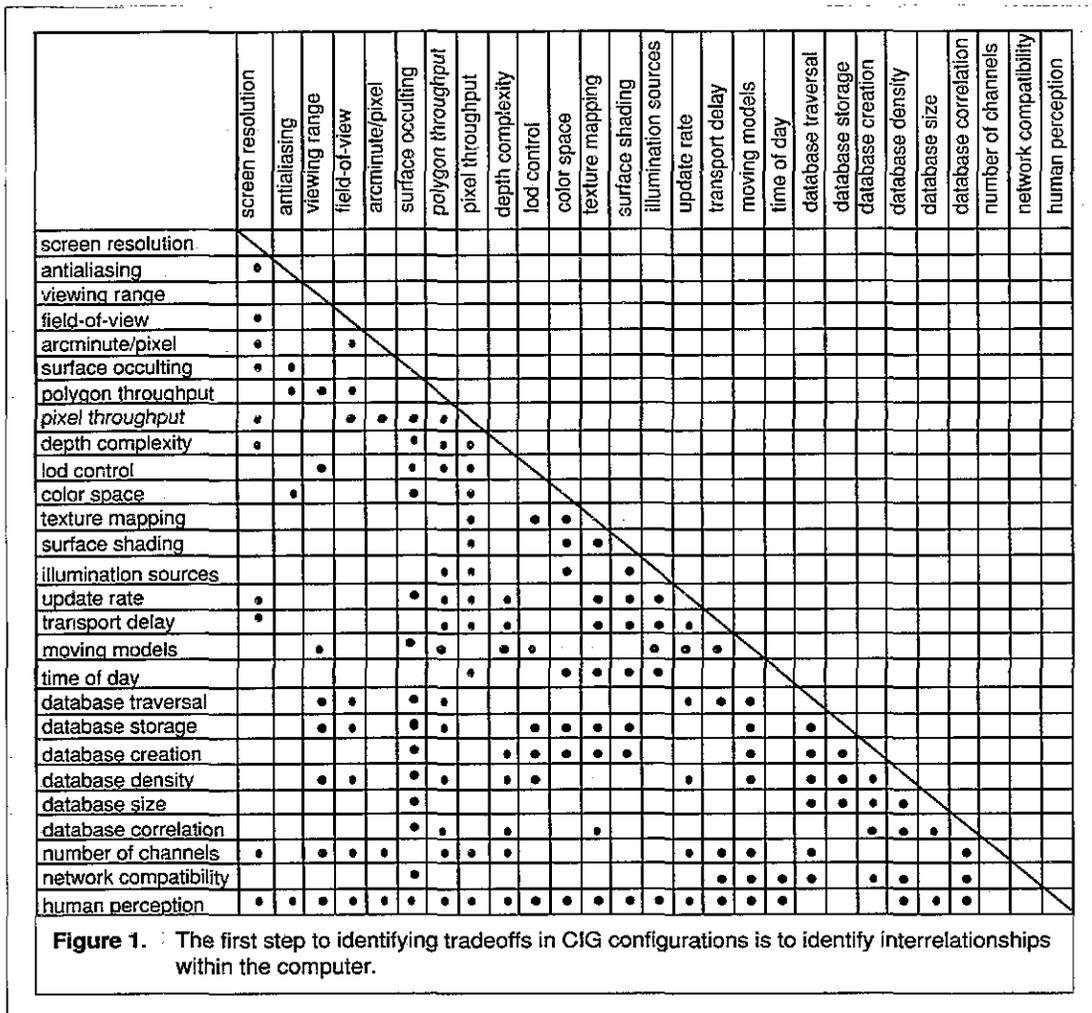
DESCRIPTION OF CIG GRAPHICS PIPELINE

In order to clarify tradeoffs within the CIG, it is useful to understand the general processing sequence of real-time graphics creation. For the purpose of discussion, I will describe a hypothetical CIG system with a graphics pipeline as shown in Figure 2.0. This system has a front end processor that interacts with an external simulation host com-

puter. The front end processor is typically real-time software running on an embedded CPU. The functions it handles include message decoding, moving model queuing, database traversal, level of detail control, field of view calculations, and preliminary graphics processing such as polygon ordering.

Some CIG's will have an embedded CIG host computer that can interface directly with vehicle control inputs. Others will off-load tasks from the simulation host computer such as collision detection, height above terrain feedback, altitude information, and ballistics impact computation.

As the name implies, the graphics pipeline is a sequential path. The graphics pipeline includes the polygon processor, pixel processor, a frame buffer of some kind, and a video output stage. Some systems can take advantage of embedded parallelism of graphics pipelines to become less subject to overloads along a single path. [2]



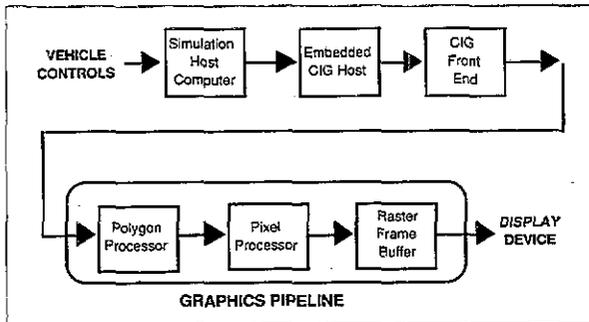


Figure 2. Performance Tradeoffs in Real-time computer graphics can occur from bottlenecks and internal overloads within a CIG computer.

The polygon processor will transform geometric entities (polygons) from gaming area coordinate system and project them to the screen space coordinate system. The pixel processor tiles or fills in the screen polygons with color or texture, performs hidden surface elimination and anti-aliasing. The frame buffer stores the pixel information, and the video output stage converts the raster pixel data to a video signal.

CIG SYSTEM BOTTLENECKS

Bottlenecks in any one of the graphics processing steps can severely effect overall graphics performance in simulation applications. If the front end tasks of the CIG become too demanding, the graphics performance may fall off due to things like data contention of a common bus, or the need for sequential processing. If a CIG system requires sorting for hidden surface removal, complex collections of models or multiple moving objects in the scene, this could cause extra time to be spent in sorting, resulting in lower polygon and pixel throughput.

Another example of potential bottlenecks can be found in single sequential path polygon and pixel processors. In a typical simulation scene, polygons are either processed from front to back or vice versa. If processed front to back, the near field polygons are larger in screen space than those in the far field. This means that the polygon processor can transform more polygons than the pixel processor may tile. When the far scene is processed, polygons are smaller but more numerous and the tiler may tile more polygons than the polygon processor can transform.

Performance specifications provided by visual system manufacturers may be based on benchmarks that have optimum sized polygons that maximize throughput of all graphics processor steps. These may not apply to real-time simulation applications.

SIMULATION APPLICATION SPECIFIC TRADEOFFS

The first tradeoff I will discuss involves creating multiple channels from a single CIG. This is common in order to add field of view for aviation applications, or to add viewing ports for armor vehicle simulations. This tradeoff requires a subdivision of a fixed computing capability that is a linear tradeoff at best.

For example, consider a CIG graphics pipeline that can produce 100,000 polygons, and 40 million pixels per second. This means the single channel would produce approximately 3325 polygons per frame at 30 Hz, and have a 512 by 512 display with a depth complexity of 2.37. If applied to a single channel, these specifications may apply, but if the same graphics pipeline produces two channels, the polygon and resolution specifications will be reduced by half. The polygon throughput would be 1650 polygons per frame at 30 Hz, and the resolution would be 512 by 512 with a depth complexity of only 1.27. Therefore, the resulting graphics processing may be inadequate for the intended application. The polygon processing could overload because of the density of the database, or the pixel processing could overload due to high depth complexity. The frame update rate could be traded from 30 Hz to 15 Hz to retain the preferred graphics processing specifications.

When adding channels of equal fidelity, added graphics processing power or changes in the CIG configurations are needed. This simple tradeoff is probably the most overlooked relationship.

CIG TRADEOFFS AFFECTING HUMAN VISUAL PERCEPTION

Human visual perception of a raster image directly relates to the ability of crew members to perform the required training tasks. Image effectiveness can be directly correlated to spatial dynamic queuing based on changes in the scene. Therefore image effectiveness is directly tied to image complexity and image fidelity. Image complexity is related to the polygonal density in the database, the shading technique of polygon surfaces, and the surface texture on polygons. These features influence the perceived number of edges within the scene. The image fidelity is related to the computed screen resolution, and pixel antialiasing. [3] [4] These features influence the sharpness of the perceived image.

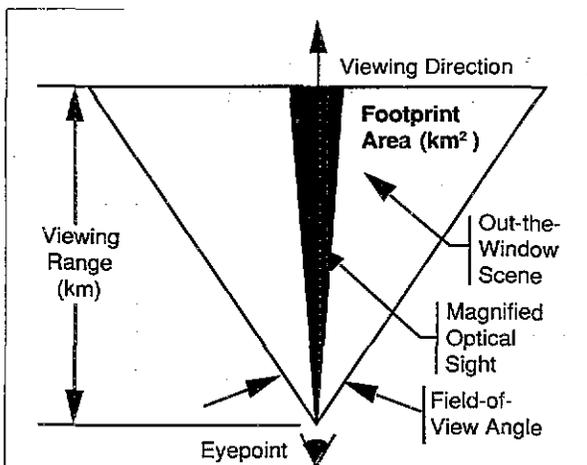
TRADEOFFS FOR IMAGE COMPLEXITY

This section discusses the relationship of the configuration parameters of viewing range and field of view to the graphics performance parameter of polygon throughput, and polygonal density of the gaming area database. [5]

The polygon throughput of a CIG is typically a finite processing capability, so I will assume this as a constant for a given channel. If the polygon processing requirement exceeds the capability, some kind of overload will occur. Overload conditions result in reduced frame rate, lower levels of detail, flashing, or polygons dropping out of the scene. None of these are really acceptable.

Polygon throughput is primarily related to viewing range, field of view angle, and polygon density in the gaming area. Secondary considerations include back face elimination, level of detail control, overload control, and moving models. These factors affect image complexity uniformly in most scenes. For the purpose of this discussion, I will examine only the primary factors that apply to the static scene to be processed by the CIG.

The CIG must process all potentially visible polygons within the footprint area as shown in Figure 3. The relationship of these CIG configuration parameters is defined by Equation 1.



$$\text{Footprint Area} = \text{Range}^2 * \tan(\text{Field of View Angle}/2.0)$$

Figure 3. Magnified optical sights have much smaller footprint areas due to narrow fields of view. The footprint area is defined by the viewing range and field of view. This value is used to determine the polygon density in the gaming area. Lowering polygon throughput for a CIG or raising database densities can be used as a tradeoff.

Equation (1)

Throughput \leq Footprint Area * Density where:

Footprint Area = $(\text{Range}^2) * \tan(\text{HFOV}/2.0)$

Throughput = Required Polygon throughput of static scene

Range = Maximum Viewing Range (KM)

HFOV = Horizontal Field of View (Degrees)

Density = Polygon Density of Gaming Area
(Polygon/Kilometers²)

Increasing the maximum viewing range and/or the field of view (Figure 4) results in a dramatic reduction in database density as shown. The database density, in turn, has a direct effect on the scene complexity of the image. If a common correlated database across multiple channels is a design goal, adjustments should be made in viewing range, field of view, and polygon performance per channel.

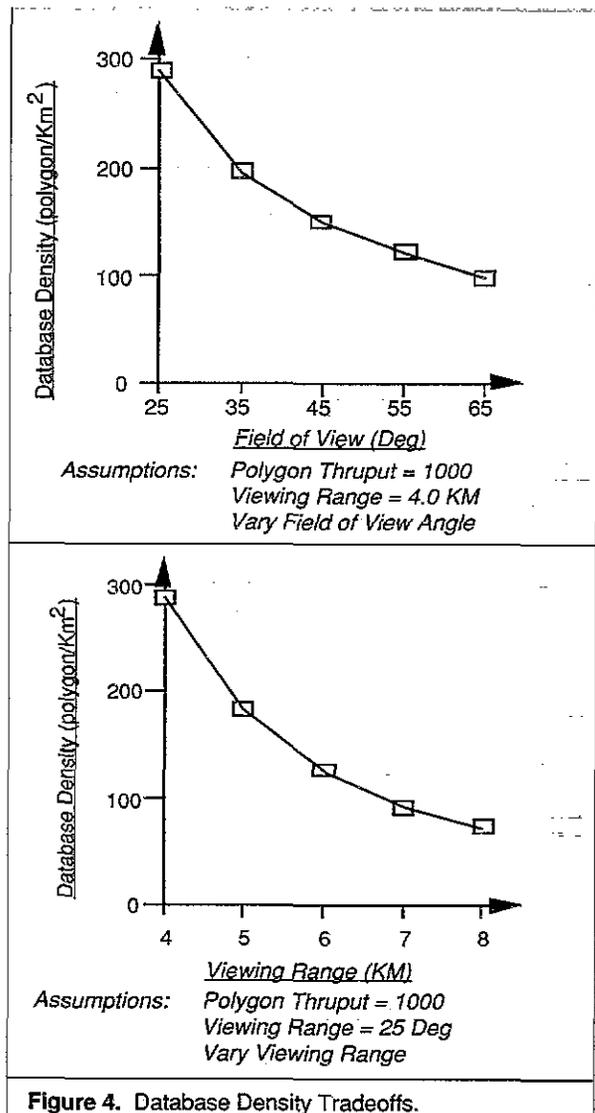


Figure 4. Database Density Tradeoffs.

TRADEOFFS FOR IMAGE FIDELITY

The purpose of discussing this interrelationship is to understand the baseline visual system resolution needed to conduct adequate simulation and training. The image resolution requirements should be defined on the basis of tasks for the crew members at each particular display. The visual system display configurations will differ from crew position to crew position due to the different task performance requirements and field-of-view specifications. For example, typical visual channel parameters for a tank simulator are shown in Figure 5.

Crew members such as the gunner and tank commander need to detect, recognize, and identify targets within specified ranges. This is accomplished by looking through periscopes with the

unaided eye, and by looking through magnified optical sights. The ability of the crew members to accomplish these tasks is based in the Arcminute per Pixel (AMPP) ratios.

A driver, on the other hand, needs only to detect objects at close range in order to navigate the tank properly around obstacles. The driver vision blocks (periscopes) have typically much wider fields of view than the sights, but the driver's visual display needs, such as target detection, are much less.

The horizontal and vertical field-of-view angles define the viewing pyramid for the visual system channels as shown in Figure 6. The FOV angular measurement divided by the screen resolution is the arcminute per pixel (AMPP) ratio. This ratio can be used as an initial guide to image fidelity.

Visual Channels	Crew Station	Field-of-View (Deg)		Resolution (Pixel)		AMPP Ratio
		Horiz	Vert	Horiz	Vert	
Gun Sight	Gunner	5.00	3.75	640	480	0.47
Thermal Sight	Gunner	4.75	2.37	640	320	1.34
Thermal Sight	Gunner	14.25	7.12	640	320	0.45
Each Vision Block	Gunner	13.00	7.00	640	480	1.22
Each Vision Block	Driver	45.00	15.00	640	200	4.21
Night Vision	Driver	45.00	15.00	640	200	4.21
Vision Block	Loader	45.00	15.00	640 <td 200	4.21	
Sight	Commander	27.00	20.25	640	480	2.53
Sight	Commander	7.20	5.40	640	480	0.68
Gun Sight (12x)	Commander	5.00	3.75	640	480	0.47
Thermal Sight	Commander	4.75	2.37	640	320	0.45

Figure 5. Typical Tank Simulator Visual Channel Parameters for Crew Stations.

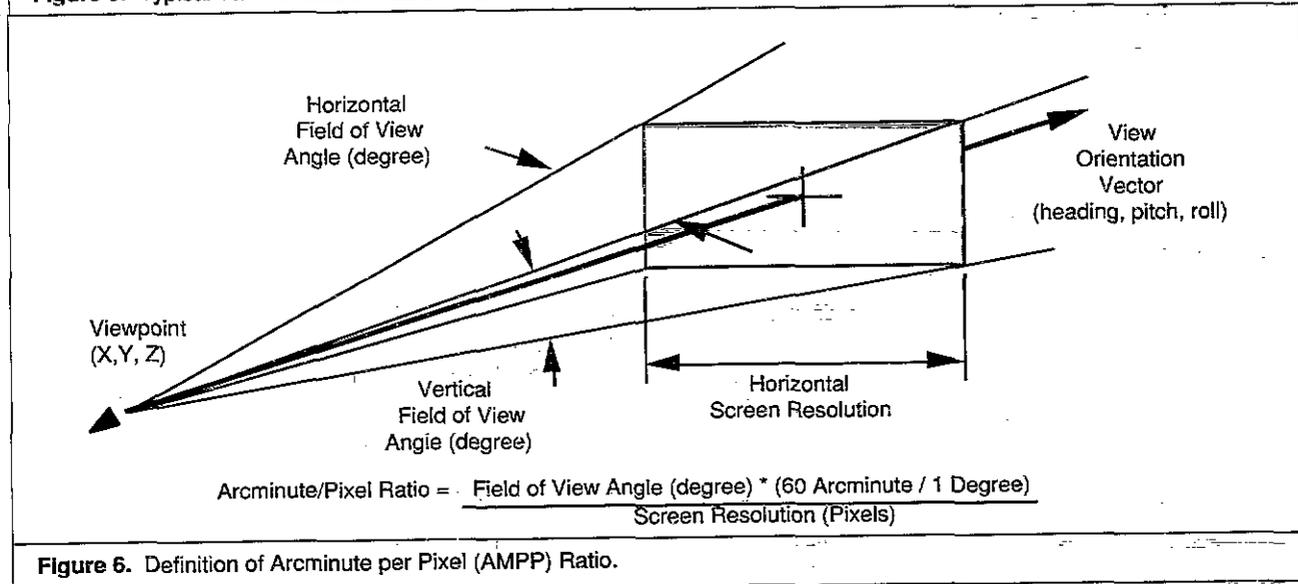


Figure 6. Definition of Arcminute per Pixel (AMPP) Ratio.

In order to match the crew member's visual needs to the parameters of resolution and field-of-view, criteria of human performance called the Johnson's Criteria are used. [3] These criteria determine the resolution requirement for minimum object dimension versus human discrimination levels as shown in Figure 7 and described further in Figure 8. [3]

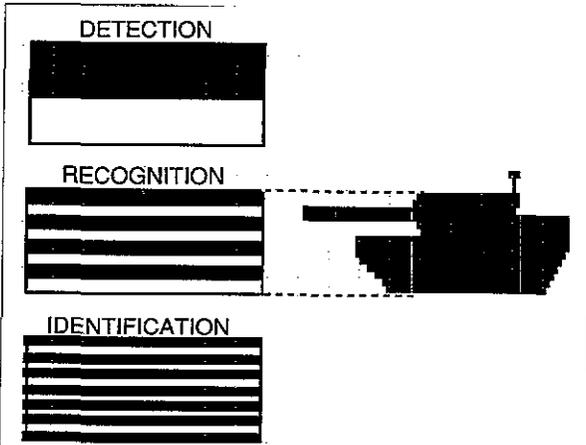


Figure 7. Resolution requirement per minimum object dimension to achieve a level of object discrimination expressed in terms of an equivalent bar pattern.

The Johnson's Criteria are defined by Equation 2.0 [3].

Equation (2)

$$\text{Target Resolution Criteria} = (D/R) * (180/\pi) * (N/FOV)$$

D = Minimum Dimension of the Target (Meters)
R = Range of the Target (Meters)
N = Image Resolution (Pixels)
FOV = Field-of-View Angle (Degrees)

The resolution requirements of the Johnson's Criteria correspond to the number of pixels of the target in the minimum dimension on the screen. The object size (pixels) on the screen will vary for displays at different magnifications. For example, using the specifications of Figure 5, a 2.5-meter high tank target at 2000 meters will appear as a single pixel in the driver's vision block, but it will appear as 9 pixels for the gunner with a 12X magnified sight. This would be adequate to classify the target and thus engage it. This criteria is applied to a 12X magnified optical sight as shown in Figure 9.

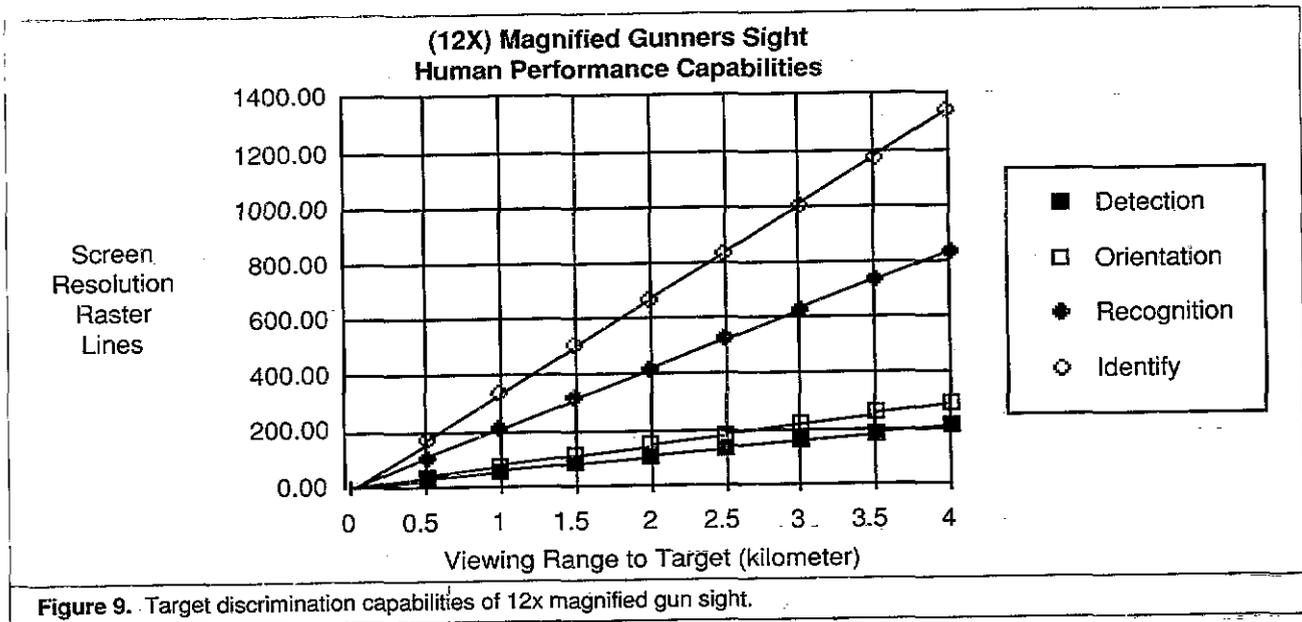
The Johnson's Criteria are an analytical approach to determining the human performance

LEVEL	DESCRIPTION	RESOLUTION OF TARGET (PIXEL)
Detection	An object is present.	2.0
Orientation	The object is approximately symmetrical or asymmetrical and its orientation can be discerned.	2.8
Recognition	The class to which the object belongs can be discerned (e.g., house, tank, man).	8.0
Identification	The target can be described to the limit of the observers knowledge (e.g., motel, T-72 tank, soldier).	12.8

Figure 8. Resolution requirement for minimum object dimensions versus human discrimination levels.

capabilities of target detection, recognition, and so on. BBN has observed that in a distributed simulation environment such as the SIMNET tank simulation, the crew member can perform these tasks at lower resolutions and even greater ranges. [2] [6] This is due in various degrees to the following factors:

- Antialiasing of image reduces raster effects [4]
- Imagery is color versus black/white for added color contrast [7]
- 3-D perspective texture adds depth perception cues
- Special effects such as smoke and dust trails enlarge targets
- Moving targets and viewpoints add to parallax visual cues [7]
- User interpretation based on reasonable probability in scene
- Targets are rarely in worst case orientation as specified in the criteria [7]
- Crew members are experienced in crew tasks for tactical situations [7]



CONCLUSION

In this paper I have described the interrelationships between CIG system parameters and some of the tradeoffs involved in getting around potential bottlenecks. I have also discussed human visual perception and the relationship between training applications and CIG parameter tradeoffs.

This information can be used in the selection of a CIG by developers of simulation and training systems. The primary objective of the simulation system must be training effectiveness for each crew member. With this in mind, the recommended steps to take in configuring a visual system are:

1. Identify the crew member training needs at each individual display station.
2. Evaluate the physical requirements such as the number of displays, and fields of view.
3. Prioritize the CIG performance requirements.
4. Identify possible problems and bottlenecks.
5. Make application specific parameter tradeoffs to get around bottlenecks.
6. Select the CIG that best matches application specific parameter tradeoffs.

As a final example, consider an armor vehicle simulator with a gunner and driver crew station. The task is to configure a visual system that maximizes the scene complexity and fidelity that achieves proper

training objectives. The system configuration goals include using the same basic visual system, and a correlated gaming area database for each crew station.

1. The driver is required to navigate the vehicle around obstacles, navigate, and follow the commands of the other crew members. The gunner is required to detect, classify, and engage targets at specified ranges.
2. The driver has three periscope displays, each with a wide field of view such as 60 deg by 15 deg. The gunner has a single gunner's sight that has two magnified optical settings with fields of view such as 5.0 deg and 14.0 deg respectively. The gunner's screen resolution aspect ratio must be 1.0 to prevent distortion for magnified views. The driver's screen resolution aspect ratio can approximate the physical periscope field of view parameters.
3. Both crew members need high image complexity. The driver needs many objects in the near field to simulate actual obstacle densities. Objects in the far field can be simple in geometry. The gunner needs high detail target models for identification, and a dense gaming area to provide proper cover and concealment of targets in the gaming area. [8] The gunner in particular needs high screen resolution to achieve his target detection, recognition, and identification tasks.

4. The potential bottlenecks for the CIG are major differences in fields of view that adversely affect database density requirements of the two gaming areas. The other problem is that the resolution requirement of the gunner would likely be overkill for the driver to perform driving tasks.
5. The first area I would examine is the resolution requirements of the gunner based on target size and recognition ranges needed for training. By using the Johnson's Criteria, the pixel throughput is determined. Lets say that 750 by 750 pixels is needed with AMPP ratios as low as 0.40. If the CIG produces 1024 by 1024 pixels, the added pixel capability should be preserved to improve depth complexity of the scene. It is likely that the total pixel area of the gunner's display can be re-allocated across three driver periscope displays due to the closer range of obstacles in the near scene. The required AMPP ratios of each display may be as high as 4.5 and still allow proper driving tasks. The screen resolution requirement for each of the driver's periscope displays may be as low as 800 by 200 pixels.

The system is now configured so that a single CIG is dedicated to the driver's visual displays and another to the gunner's visual displays. Now we consider the largest gunner's field of view and maximum viewing range to determine the gunner's viewing footprint area. This value and the polygon throughput of the single channel CIG can be used to determine the maximum database density that could be handled by the gunner's displays. For the gunner's three channel displays, divide the single channel polygon output by three to determine the polygon output for each display. This value and the periscope field of view would determine the maximum database density that could be handled by the driver's displays. The driver's maximum viewing range should be adjusted inwards to match the database density requirements of the driver and gunner to achieve a correlated database with similar image complexity. Another option would be to reduce the driver's image update rate to allow more computation time to process polygons and pixels.

As the requirements to simulate vehicles with heterogeneous visual display requirements increases, the need for understanding tradeoffs in CIG products increases. Visual system product costs are from 20% to 50% of recurring simulator costs; therefore, proper specification and configuration can permit the achievement of training objectives while substantially reducing costs in simulation systems.

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