A LOW-COST VISUAL SENSOR SIMULATOR

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INTRODUCTION

Pilot acceptance studies of Digital Avionics Information System (DAIS) concepts, conducted by the Air Force Flight Dynamics Laboratory, required cockpit presentation of typical forward looking sensor imagery. The objectives of the studies were to verify that the DAIS concepts do not jeopardize safety-of-flight integrity, measurably degrade performance of flight control configurations, nor degrade the pilot effectiveness. At the same time, the resulting system must not only be usable but be fully acceptable to the pilot. The AF Flight Dynamics Laboratory DAIS Simulation Facility was developed to accomplish these objectives through subject testing, using a replication of a Close Air Support aircraft cockpit. The program plan for the DAIS Simulation Facility includes both a stand alone capability and integration with the FDL Terrain Board Facility which will provide a projected televised view of the simulated flight path terrain for direct pilot viewing through the cockpit window. To enhance the realism of the cockpit environment, typical visual sensor imagery was required which would be representative of forward looking radar, low-light-level television and forward looking infrared sensors, corresponding, in real-time, to the projected scene. A Visual Sensor Simulator, described in the following sections, was developed by Technology Incorporated to provide a low-cost solution to this requirement. By processing the terrain board video signal in real-time through the use of analog circuit techniques, simulated radar and electro-optical sensor imagery was generated which has been highly acceptable to experienced pilots.

The Visual Sensor Simulator was designed to present representative imagery and not actual target signatures. The design study was based on various target signature data but the correlation of sensor return for comparison of target signatures was not included in the initial program plan. Future studies are planned to investigate these requirements in conjunction with other programs.

DESIGN CONSIDERATIONS

The present version of the Visual Sensor Simulator was designed to be operated with a direct terrain board video signal, although other input signals are feasible. A generalized application is shown in Figure 1, where the primary electrical signal is provided by a TV vidicon that is responding to a visual scene generated either from a terrain board, a motion picture, or a video tape recording. The sensors considered in this discussion will be forward looking IR (FLIR), forward looking, real-aperture radar (FLR), low-light-level TV (LLLTV), and synthetic aperture radar (SAR).

Any realistic sensor simulation should approximate those sensor parameters that are of significance to the human observer. In Figure 2 a general sensor configuration is presented, including the elements of scene definition, atmospheric effects, and specific sensor characteristics. Scene definition includes the significant parameters (e.g., resolution, reflectivity $R(\lambda)$, emissivity $\varepsilon(\lambda)$, thermal inertia, object contrast) that are of importance within the spectral region of the sensor; atmospheric effects include all noise and spectral dependent attenuation effects; finally, the sensor itself is defined as a complicated function of S/N ratio, modulation transfer function $M(f)$, signal compression, and various other special sensor effects. Consistent with the sensor model of Figure 2, each of the four sensors will be defined in terms of operating S/N, modulation transfer function, signal compression properties, and relevant special effects. Referring to Figures 1 and 2, the primary analog sensor-simulator input is, in all cases, generated from a vidicon and is, therefore, restricted to target reflectivity properties, $R(\lambda)$, in the visual spectral region; any useful simulator, whether analog or digital, must make a correlation between the visible $R(\lambda)$ and those target properties relevant to the particular sensor (e.g., $\varepsilon(\lambda,T)$ for FLIR and $R(\lambda)$ in the microwave region for FLR).

ANALOG CIRCUIT TECHNIQUES

For the cockpit simulator application, it is assumed that the primary TV signal will be initially noise-free ($S/N = \infty$) and that the raster scan pattern will be roughly 600 lines, 30 frames/sec or equivalently 5 MHz in video bandwidth.

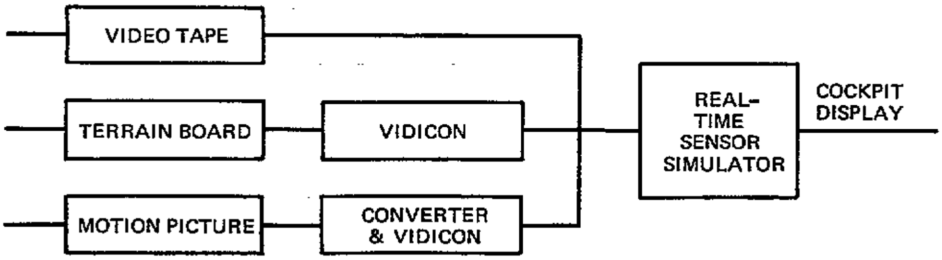

Figure 1. Sensor Simulation Application

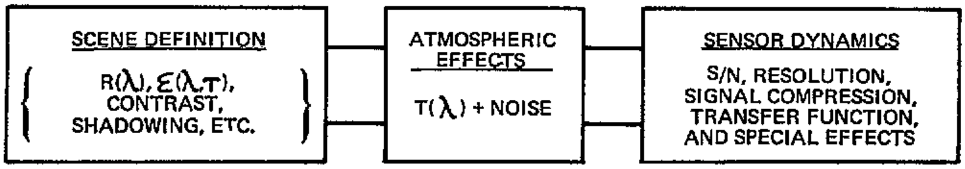

Figure 2. Sensor Modeling

Figure 3. General Single-Channel Processor

Analog circuit components process each TV raster line sequentially with the processing performed by a cascade of high performance, operational amplifier-based processing elements. Utilization of OP-AMP processing at video bandwidths is made possible by the recent availability of wide-band, high slew-rate operational amplifiers. Figure 3 illustrates the general single-channel processor where the heart of the processor is the "OP-AMP" processor unit henceforth referred to as "the single-channel processor." The single-channel processor begins with an OP-AMP signal-plus-noise summation where the raster signal format is added to a flat spectrum, level-controlled noise source as shown in Figure 4. The next stage is the edge enhancer which is essentially a differentiator and is used to simulate "hot spots" in FLIR and specular returns in both FLR and SAR coherent radars. The next processing unit simulates the overall linear sensor transfer function, M(f), by means of a flexible, active filter. The final processing unit is usually a zero-memory nonlinearity (ZMN) designed to simulate signal blooming, gray-level compression and target $R(\lambda)$, $\varepsilon(\lambda,T)$ effects; ideally, the ZMN unit should have independently set slopes and breakpoints as illustrated in Figure 5.

Utilizing wideband operational amplifiers, acceptable simulations for the sensors were achieved by using the "single-channel processor" described above in a breadboard version. For the second generation simulator, a "two-channel processor" capable of selectively processing targets and background was developed. In order to implement this two-channel processor, it is necessary to detect targets in real-time and, with proper time phasing, switch between a target processor and a background processor. Because all useful target signatures require the entire target history (e.g., width between sharp edges, magnitude, target modulation, etc.), the principal signal path of the two-channel processor must be delayed by some fixed amount (Figure 6) while the target/background decision is being made. Fortunately, low distortion, video time delays are now available in the 0 to 10 microsecond range. The target detection circuit and related timing circuits are entirely digital and control high-speed CMOS analog switches with switching times on the order of 10-20 nanoseconds.

SENSOR CHARACTERISTICS

Despite the generality of the one- and two-channel processors, the specific features of the individual sensors must be considered in any useful analog sensor simulation. The following exposition is a sensor-by-sensor discussion of how each sensor is simulated using the analog approach.

Forward Looking Infrared (FLIR)

The major challenge for an analog FLIR simulation is the accurate modeling of scene thermal emissivity. A truly accurate TV-derived FLIR simulation must somehow relate visual reflectivity to IR emissivity, and in addition, account for thermal inertia effects. Analytically, the TV terrain responses can be expressed in integral form as:

$$I_{TV} = k_{TV} \int_{\lambda_3}^{\lambda_4} R(\lambda)\ C(\lambda)\ d\lambda$$

where the limits, λ_3 and λ_4, represent the visual wavelength region for TV response, $C(\lambda)$ is the atmospheric transmittance, and k is a constant, including illumination, etc. The corresponding FLIR output can be expressed as:

$$I_{FLIR} = k_{FLIR} \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda)\ C(\lambda)\ B(\lambda,T)\ d\lambda$$

where $\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4$.

Despite the difficult thermal inertia problem, a relationship does exist between $\varepsilon(\lambda)$ and $R(\lambda)$ in the form of Kirchoff's law; namely, that $\varepsilon(\lambda) + R(\lambda) = 1$ or that emissivity and reflectivity sum to unity. While this relationship does not directly solve the problem, inasmuch as the visual and IR wavelength regions are different, it does indicate that bright TV areas will in general be dark in the IR image. Given this somewhat "loose" situation, a reasonable approach is a two-channel configuration where the respective ZMN's are calibrated according to the ensemble averages of the target/background emissivities. Since the ZMN's are easily altered by pot adjustments, experience can be quickly gained from calibrating real-life TV, FLIR runs.

Another characteristic feature of FLIR imagery is the presence of "hot spots" on man-made targets, e.g., tanks and trucks. One possible method of simulating the "hot spot" is to edge-enhance the characteristic sharp edges of the manmade object and then limit the output of the enhancer with a zero-memory nonlinearity. With a raster scan pattern of variable orientation, a very realistic simulation of the "hot spot" feature can be achieved.

Additional features of an analog FLIR simulation are the "white-hot," "black-hot" options which can be easily simulated using a simple inverting amplifier and also the presence of the faint raster scan pattern

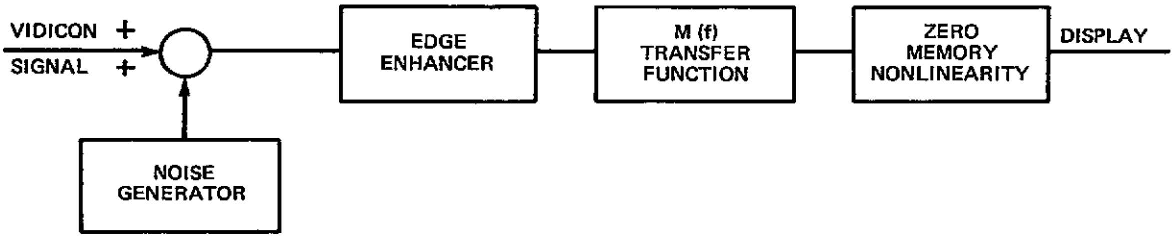

Figure 4. Single-Channel Processor

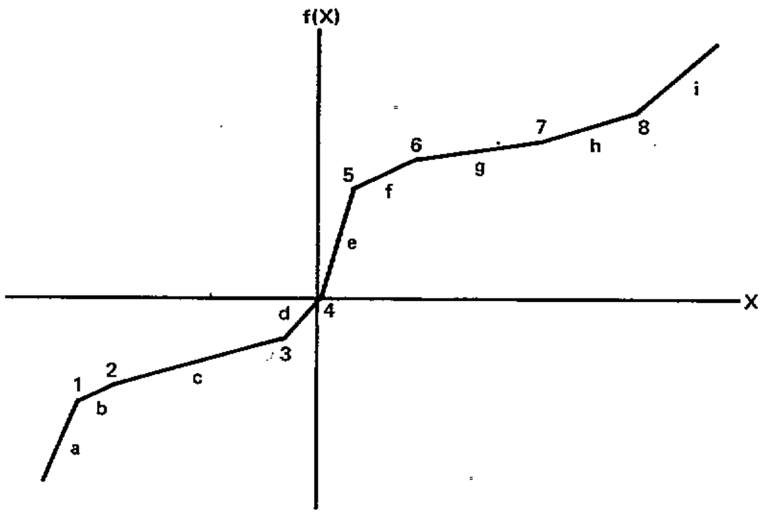

Figure 5. Ideal Zero-Memory Nonlinearity

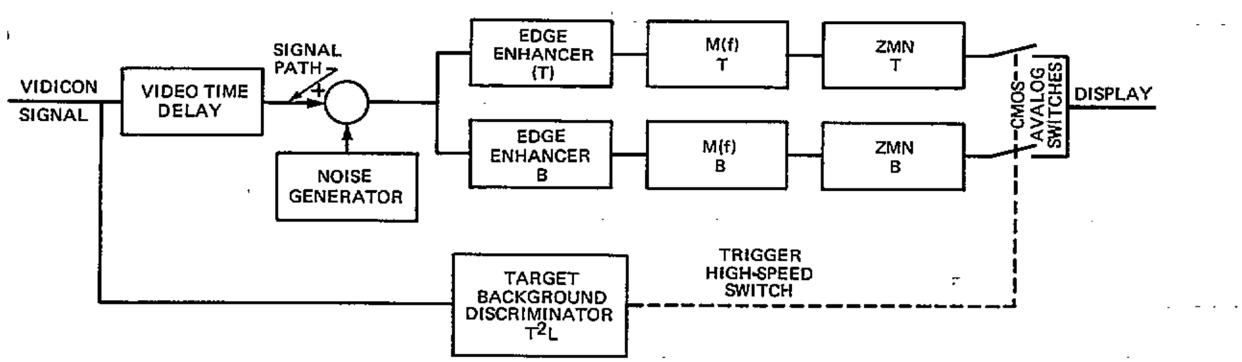

Figure 6. Two-Channel Processor

(nonuniform IR detector mosaic) which can be simulated using a special-purpose circuit synchronized with the vertical and horizontal sync pulses.

The specific two-channel FLIR configuration is shown in Figure 7. It is observed that the edge enhancer is eliminated from the background channel in order to avoid producing an unnatural appearing "sharpness" in the background.

Low-Light-Level Television (LLLTV)

Because the LLLTV sensor responds to the same $R(\lambda)$ as the vidicon, no distinction need be made in the processor between target and background classes. As a result, the preferred simulator configuration for LLLTV is the single-channel configuration. For the analog simulator, the LLLTV features of special interest are signal "blooming" and the image-lag effect. Since signal "blooming" is a result of saturation in the final display stage, the "saturation" ZMN in the LLLTV simulator must be positioned at the last stage after the noise has been added and the signal has been processed through the linear transfer function. The linear transfer function itself will be a cascaded pair of linear operations, the first of which is the time invariant modulation transfer function, $M(f)$, and the second of which is the velocity dependent image-lag operation. The image-lag operation will have an impulse response given in Figure 8 and will be realized with a wideband video delay line as shown in Figure 9.

The overall single-channel LLLTV simulation is presented in Figure 10.

Forward Looking Radar (FLR)

In a typical real aperture PPI display the targets are "blips" against a dark background and are narrow in the range direction but wide (beamwidth times range) in the azimuth direction. Although the PPI display is clearly the appropriate display for a polar coordinate-based system, any coordinate transformation from the rectangular coordinate, as raster scan to the PPI, is virtually impossible for an analog system without scan-to-scan memory. Fortunately, at the longer slant ranges, where the cueing operation is desired, slant range is about the same over the entire ground patch and the coordinate problem is no longer present, permitting the direct use of a rectangular scanned CRT display. The broad flow of a two-channel FLR simulator is to selectively process the target/background classes on the basis of their ensemble averaged reflectivity coefficients, $R(\lambda)$, in the microwave region, incorporating through an edge-enhancer the important specular return nature of the target class. Both target and background signals will be summed and then fed into a video comparator to provide the "on-off," "blip" character of the signal returns. The elongation in the azimuth direction can be readily simulated with a circulating delay line, and the "painting" effect of the scanning physical antenna will be simulated with a special-purpose circuit synchronized to the horizontal and vertical sync signals. Figure 11 illustrates the two-channel FLR simulator.

Synthetic Aperture Radar (SAR)

A synthetic aperture radar simulation was not included in the final system implementation of the Visual Sensor Simulator. However, the basic circuitry design was considered as described below.

As with the FLR sensor, a two-channel SAR configuration would simulate the microwave scene reflectivity, $R(\lambda)$, with dedicated target and background ZMN's. Edge enhancers would simulate both the specular nature of the scene and the overall effect of shadowing (the edge-enhanced simulation of shadowing is quite effective provided the enhancer has a damped oscillatory (zero crossing) step response). Figure 12 demonstrates a typical SAR configuration where the final $M(f)$ simulates the IF pass-band, resulting in a lowering of the overall sensor resolution.

CIRCUIT FUNCTIONS

The hardware implementation of the Visual Sensor Simulator consolidated the desired circuit functions, system interfaces, and controls into the physical package shown in Figure 13.

The desired circuit functions, illustrated in the block diagram (Figure 14), are accomplished by utilizing medium speed T^2L, CMOS logic families and high-speed analog devices. Wherever practical, separate circuit cards were utilized for each type of sensor video, processors to provide independent adjustment and modification capability. Certain common functions, such as power, sync and noise generation which are utilized in all sensor video channels, are provided from dedicated circuit cards. Extensive bypassing and decoupling is utilized on the power supply lines to prevent instability and other anomalies which might result in degradation of the Visual Sensor Simulator performance.

The entire simulator is housed within a standard 19-inch rack and powered by 120 VAC single-phase 60 Hz power. Computer control is provided by optically isolated binary address lines. The computer interface was specially designed to provide a switchable video output capability. The interface circuit provides binary decoding and the necessary video and sync switching.

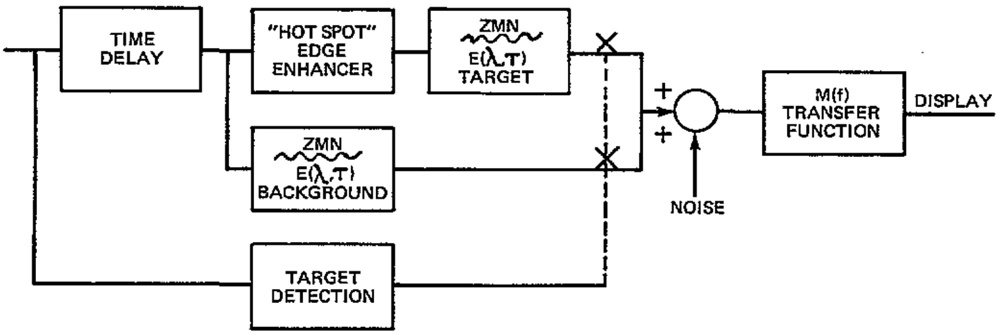

Figure 7. Two-Channel FLIR Simulator

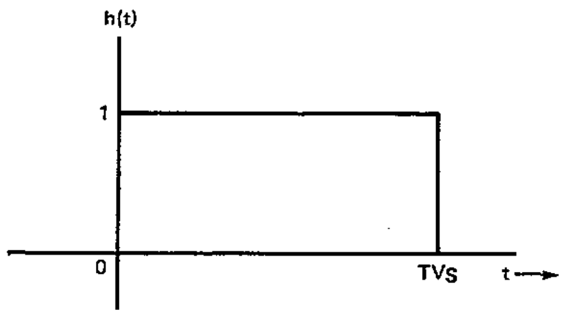

Figure 8. Impulse Response of Image-Lag Simulator

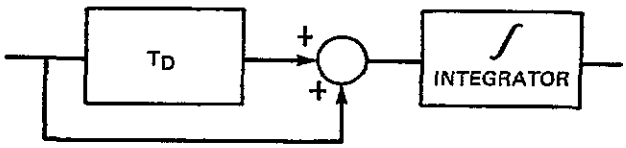

Figure 9. Image Smear Circuit Realization

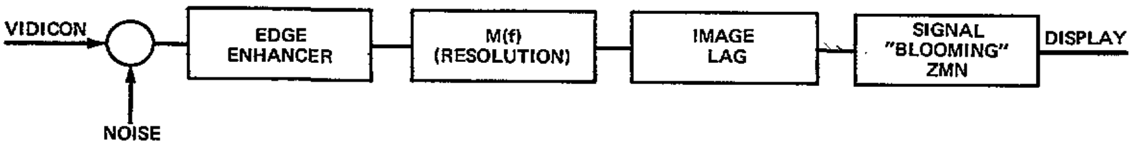

Figure 10. Single-Channel LLLTV Configuration

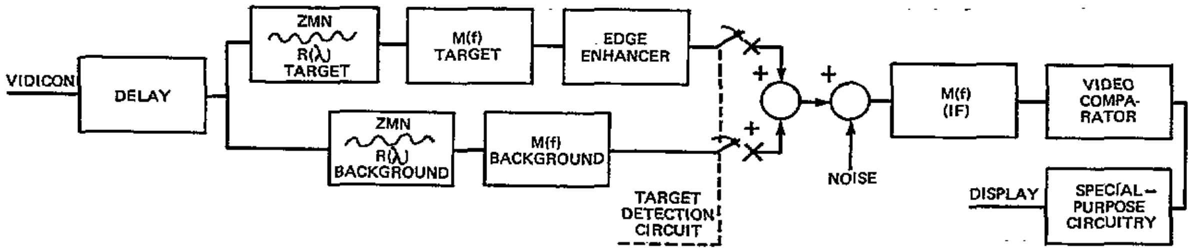

Figure 11. Two-Channel FLR Configuration

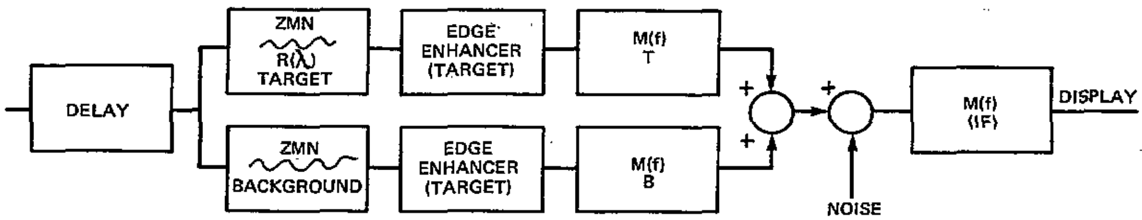

Figure 12. SAR Configuration

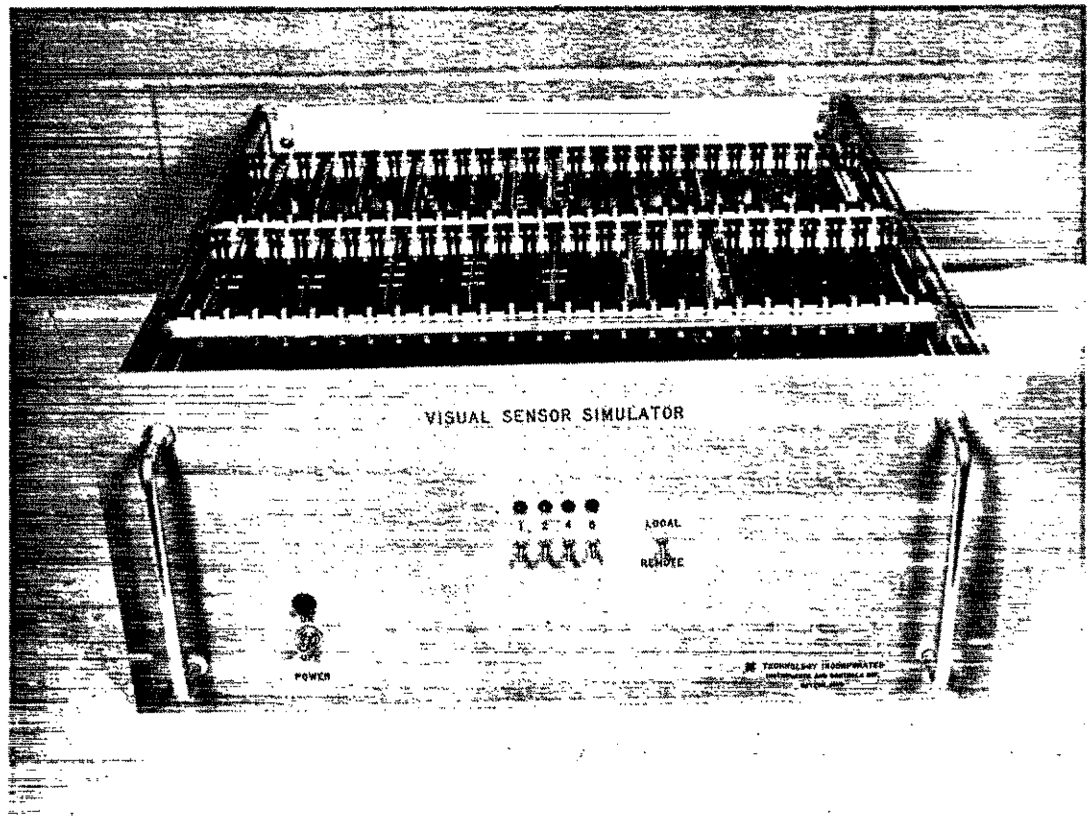

Figure 13. Visual Sensor Simulator

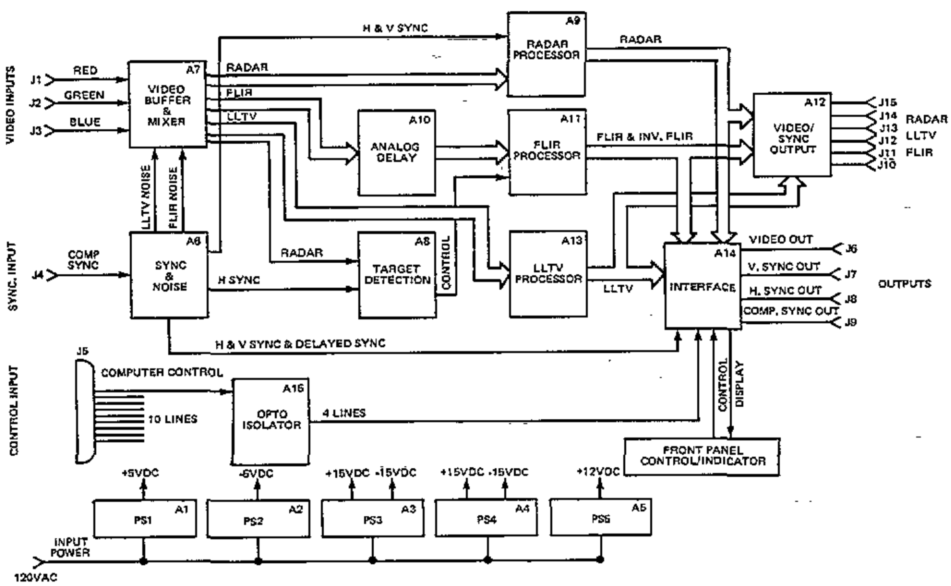

Figure 14. Visual Sensor Simulator Block Diagram

The video input circuitry is designed to accept nominal 1-volt peak, positive-going video for operation on J1, J2 and J3. For operation with RGB color video, all three input connectors are utilized.

The video input impedance is 75 ohms, but can be reconfigured to higher impedance by removal of input termination resistors on the video buffer card A7. If operation is desired on a black and white input video, the use of input connector J1 is recommended.

The sync input is designed to provide for operation with composite negative-going sync pulses (standard). The sync format may be either 525/60 (EIA Standard RS170) or 625/50 ("European Standard"). The negative-going sync input should be between 0.1 volts and 5.0 volts peak amplitude for proper operation. Operation from composite video is possible if adjustment of the sync offset control, A6R2, is performed.

Video and sync ouputs are all capable of driving a 50 foot length of 75 ohm coax cable correctly terminated at 1.0 volt video level with less than 10 percent amplitude roll-off measured at 1 MHz. Each video output has a dedicated video buffer amplifier.

Figure 15 presents an example of the representative imagery generated by the Visual Sensor Simulator. The center photo shows the original scene with the various sensor simulations shown in the surrounding photos.

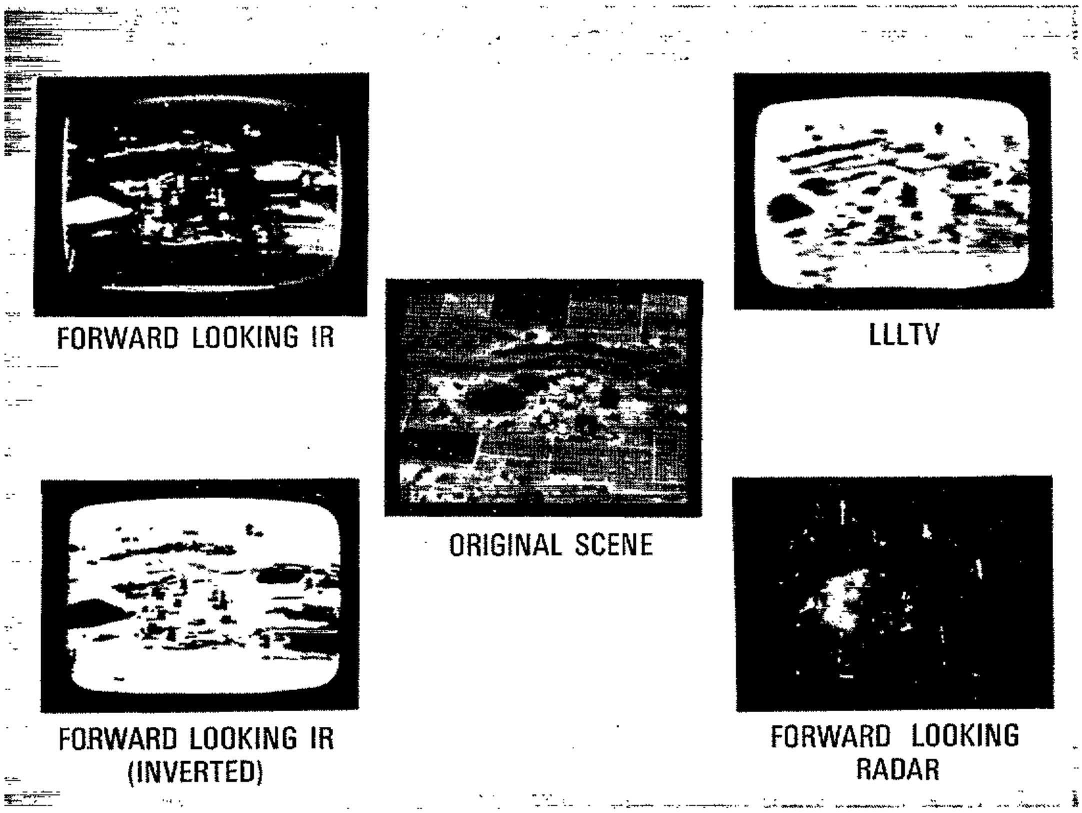

Figure 15. Visual Sensor Simulation

CONCLUSIONS

The Visual Sensor Simulator was developed as a low-cost solution to the problem of simulating airborne visual sensors for pilot-in-the-loop testing. While the present version was found to be highly acceptable for the required purpose, it was recognized that the flexibility of the analog technique would permit the development of additional capability. As is typical of research and development efforts, the available funding was limited. As funds do become available, however, the development of the growth potential that is anticipated in the unit is planned. As was previously noted, the present version does not provide a capability for target identification as the signal processing provides imagery simulation rather than target signature simulation. Further efforts will be made to improve the correlation of the simulated imagery with the return from the real world electro-optical sensor and to evaluate the degree of correlation achieved by the simulation. The addition of radar range rings, controllable target designator cursors and other capabilities can be achieved with additional analog circuits and the use of different cathode-ray tube scan techniques. Some of the proposed additional capabilities are shown in Figure 16. Further development efforts to implement these improvements are anticipated.

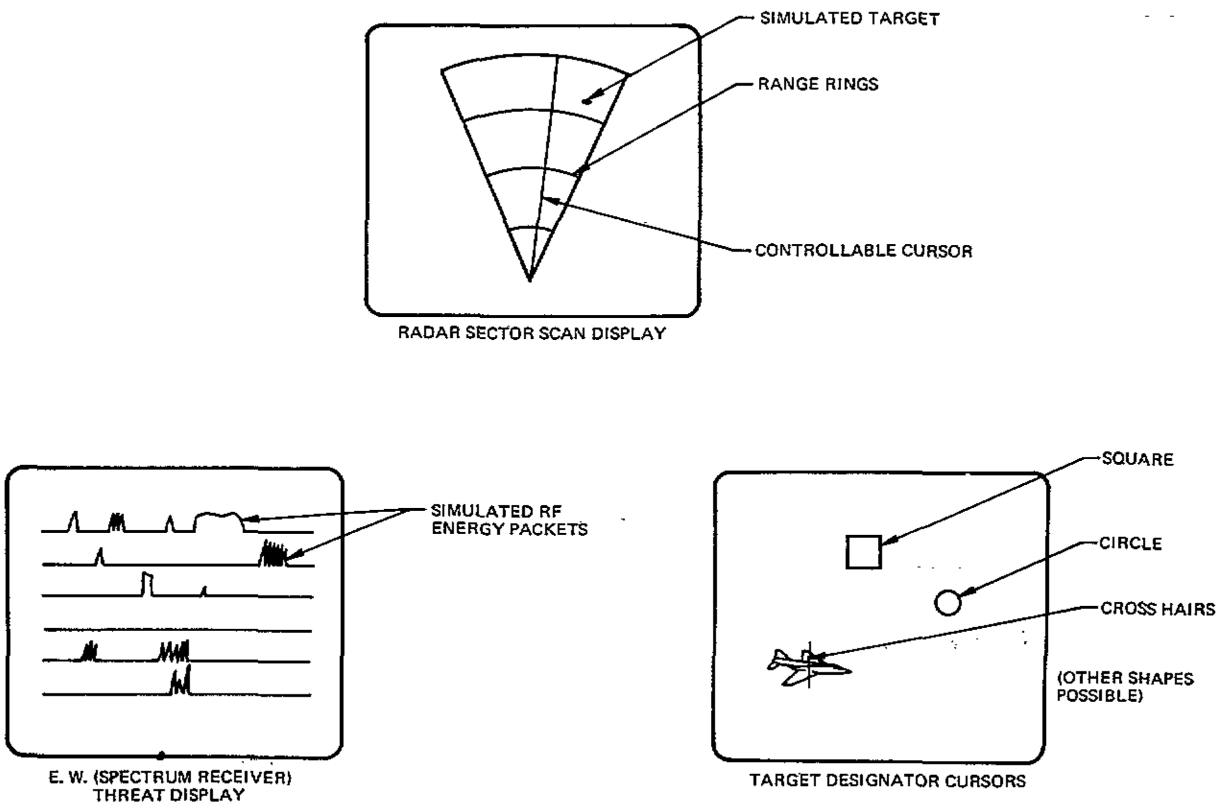

Figure 16. Proposed CRT Display Simulations

ABOUT THE AUTHORS

DR. WILLIAM McCORMICK is a member of the engineering faculty at Wright State University and a consultant for Technology Incorporated. He was primarily responsible for the design of the Visual Sensor Simulator circuitry. His previous experience as a consultant included research investigations in advanced avionics systems for the Air Force Avionics Laboratory. His educational background includes a B.S.E.E. degree from Marquette University, and an M.S. degree and a Ph.D. in engineering from University of Wisconsin.

MR. RICHARD KINNEY is a Senior Electronics Engineer in the Engineering Department of Technology Incorporated. He is responsible for the hardware implementation, detailed circuit design, and system integration of the Visual Sensor Simulator. Mr. Kinney received a B.S. degree in engineering physics from the University of Maine.

MR. WALTER MASON is a Product Line Manager for Technology Incorporated. He is responsible for the management of the Air Force program under which the Visual Sensor Simulator was developed. He is also responsible for a recently awarded Naval Training Equipment Center contract for the development, fabrication, and installation of Submarine Damage Control Trainers. Mr. Mason received a B.S.E.E. degree from University of Vermont, and an M.S.E.E. degree from Kansas State University.

DR. TONY DeTHOMAS is the Deputy Director of the Air Force Flight Dynamics Laboratory Digital Avionics Instrumentation System (DAIS) Program. He was responsible for defining the requirements for a Visual Sensor Simulator as part of the DAIS Control/Display Facility. His previous experience has been in association with the Flight Controls Division of the Flight Dynamics Laboratory. Dr. DeThomas received an M.S. degree and Ph.D. from University of Dayton.