A NEURAL-NETWORK-PROGRAMMABLE PROCESSOR FOR REAL-TIME CORRELATED SENSOR SIMULATION

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ABSTRACT

Simulation of Infra-Red (IR), Synthetic Aperture Radar (SAR), and Out- The-Window (OTW) visual imagery plays an important role in the planning and rehearsal of missions and personnel training. The challenge is to develop database and image generation systems that extremely rapidly and in real time process geo-specific Multi- Spectral Imagery (MSI) over large areas into simulated sensor imagery to achieve high real-world accuracy and sensor / OTW-visual correlation. To meet this challenge, a novel architecture called a Neural Network Look-Up Table (NNLUT) which implements spectral conversion by neural networks has been developed. The NNLUT processor is described and examples of highly correlated IR and SAR imagery simulated in real time from MSI by the NNLUT are demonstrated.

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INTRODUCTION

The simulation of sensor and Out-The-Window (OTW) visual imagery plays an important role in the planning and rehearsal of missions. Typical imaging sensors include Forward-Looking Infrared (FLIR), Synthetic Aperture Radar (SAR), night-vision image intensifier, and television camera electro-optical subsystems.

Mission and User Needs

In order to maximize the probability of a successful mission, mission personnel need to observe simulated imagery to become familiar with how the world will appear through on-board sensors as well as out the windows of their platforms before they proceed with the actual mission. This "image familiarization" procedure may be performed while planning the mission and evaluating, or rehearsing, it.

Because the simulated imagery needs to portray the real world in terms of time as well as geographic accuracy, only the most recently acquired imagery of geographic areas in the world should be used as the basis for the simulation (Figure 1). The acquired *Multi-Spectral Imagery* (MSI) data is pre-processed to compensate for sensor peculiarities and geo-positioned over stored three-dimensional (3-D) terrain elevation and model height data. The combined imagery and 3-D data is reformatted into a run-time *Image Generator* (IG) database and is then available for mission planning and rehearsal.

The challenge is to develop systems that perform such pre-processing, geo- positioning, and run-time IG database generation extremely rapidly so that the simulated sensor and OTW-visual imagery is made quickly available to mission users before it becomes outdated. The information extracted by the personnel from the simulated imagery also needs to correlate well among the sensors and OTW-visual domains. Furthermore, such processing should be easily performed by mission personnel deployed in the field - without requiring a high level of personnel expertise in simulation database modeling. And finally, the correlated sensor and OTW-visual simulation and database system should be designed to allow trade-offs between cost, fidelity, and other simulation performance measures.

Unique Sensor Simulation Approach

This paper describes a neural-network-programmable processor called NNLUT -a Neural-Network *Look-Up Table* - to satisfy such multi-sensor simulation needs. The NNLUT processor hardware and software have been uniquely implemented for accurate and real-time simulation of geo-specific, correlated, Infra-Red (IR) and SAR sensor imagery directly from multi-band, *Multi-Spectral Imagery* (MSI).

The NNLUT system approach achieves the rapid availability, high correlation, and high geo-specific accuracy of the simulated multi-sensor and OTW-visual imagery by directly processing the source MSI output by the CIG in real-time, thereby minimizing effort-intensive, non-real-time, database modeling activities (Figure 2).

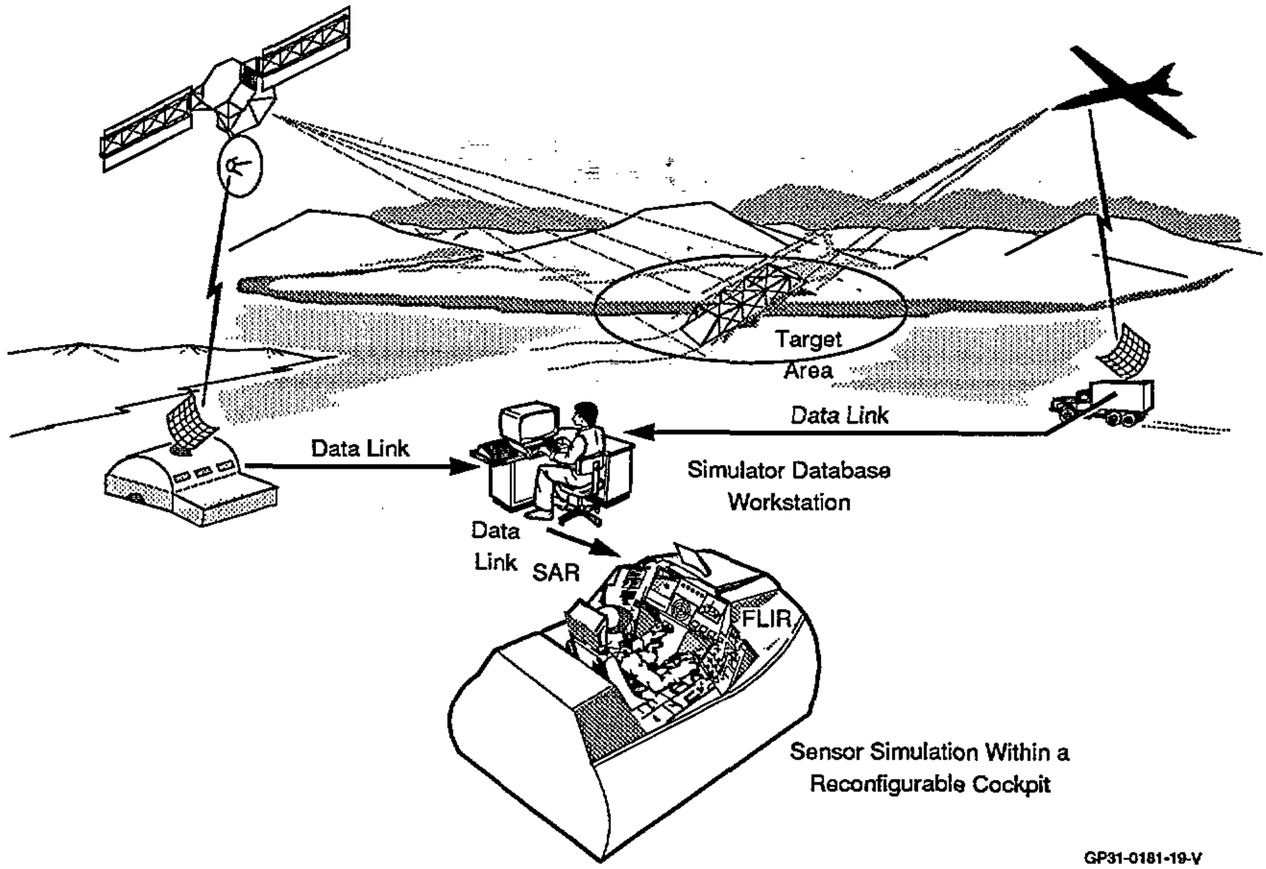


Figure 1. Field-Deployable Image Simulation Facility

The rapid simulation availability is achieved in two ways. First, generating only a single run-time IG database, rather than separate multiple sensor and OTW-visual IG databases, makes the "common" database available for real-time, direct, processing by the NNLUT.

The second way, in which rapid availability is achieved, is by directly processing geo-specific MSI over large gaming areas (backgrounds) while features and models are inserted only in small, high-interest areas. Run-time database generation steps, represented by the "Reformatting" block in Figure 2b, include geo-positioning of the input MSI over terrain elevation data using accurately known ground-control points, ortho-rectification to compensate for MSI sensor oblique view angles, mosaicking, and contrast-balancing of multiple MSI scenes into a gridded gaming area database, partitioning the MSI/ elevation database into IG texture blocks, and performing IG polygon-to- texture mapping assignments.

Geospecific accuracy is achieved by directly processing the MSI into sensor image intensities thereby preserving information relating to surface materials. This approach is in contrast to traditional sensor database generation which reduces MSI into sets of discrete material codes, attributes, and generic textures, thereby discarding valuable surface-descriptive information. This paper therefore focuses on optimal, real-time utilization of MSI for sensor image generation.

The next section describes the application of neural networks to spectral conversion based multiple-sensor image simulation. An equivalent look-up table for implementation of the neural network processing is then described, leading into a description of the real-time processing NNLUT architecture and its hardware implementation. Simulations of correlated overhead IR and SAR images as well as FLIR generated in real time by the NNLUT system are presented. Issues regarding cost vs image correlation, accuracy, and fidelity as well as NNLUT system implementation are discussed. Finally, plans for future enhancements and applications of the NNLUT system to rapid database generation and other imaging tasks are presented.

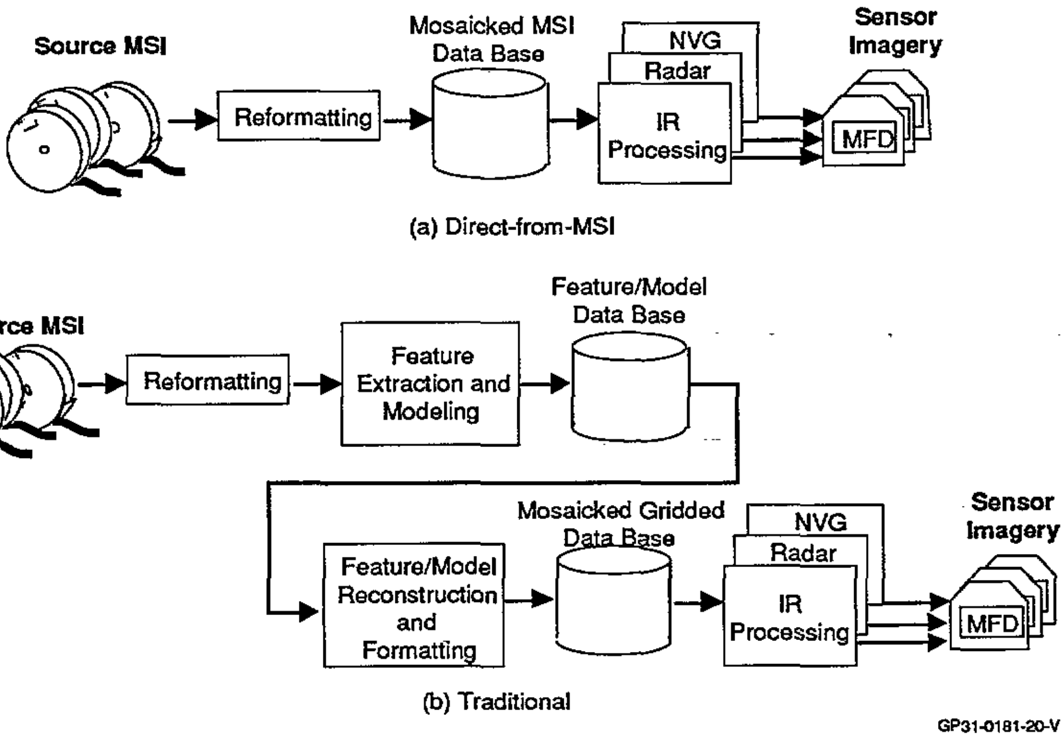


Figure 2. Direct-from-MSI vs Traditional Multi-Sensor Image Simulation

DIRECT-FROM-MSI MULTI-SENSOR IMAGE SIMULATION

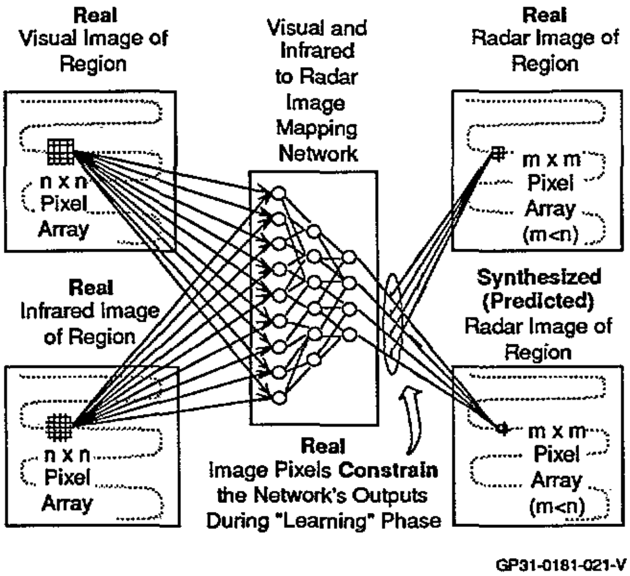


Figure 3. Neural Network Training for Direct-from-Imagery Sensor Simulation

To realize direct-from-MSI multi-sensor image simulation, the NNLUT system implements image-to-image mapping transformations, sometimes called "spectral conversion", using neural networks.

Spectral Conversion

The purpose of spectral conversion processing is to convert source MSI input intensities into the desired sensor output intensities. An MSI pixel consists of image intensities from two or more spectral bands. For example, commercially available MSI sensors produce imagery in the visible 0.5-0.7, near-IR 1.0, and a short-IR 2.4 micron wavelength bands. The desired simulated sensor pixel intensities may be in the long-wave IR 8-12 micron or 3-cm X-band radar wavelength bands.

Neural Networks

One approach to spectral conversion is to train and apply computational structures called Neural Networks (NNs) as associative memories to perform the MSI-to-IR and MSI-to-SAR inversion[1]. Figure 3 illustrates NN training to transform visible and IR-band input image intensities into radar intensities. While training, the network is iteratively presented with exemplars of corresponding visible-

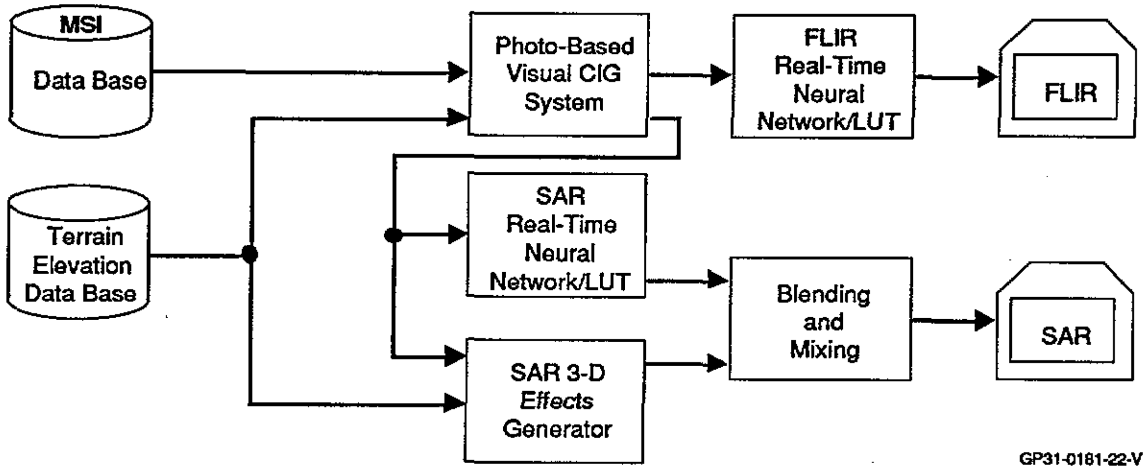


Figure 4. Correlated FLIR and SAR Image Generation from a Single MSI/Elevation Database

plus-IR input and SAR output pixels to adjust its internal weights. After the error between the predicted and actual intensities stabilizes at a minimum value, the network is ready for SAR intensities prediction when presented with similar visible-IR input combinations.

Figure 4 illustrates how the networks are used to post-process outputs from a texture-capable host Image Generator (IG) in real time. Each channel of a two-channel IG transforms the elevation and MSI texture database into an image of a scene computed from the imaging sensor's 3-D perspective. For a Forward-Looking IR (FLIR) sensor, a highly oblique terrain view is produced from one channel. The NNLUT converts the MSI pixel values output by the IG into monochromatic IR intensities. For SAR simulation, an overhead view MSI image from the second channel is post-processed by the NNLUT and the transformed image is combined with an image containing simulated SAR 3-D effects such as far-shore brightening, aspecting, and shadowing. A high degree of FLIR and SAR correlation is achieved because the same IG run-time database is used for both FLIR and SAR simulations.

To successfully implement the MSI-to-sensor transformations in real time, two key problems were solved. First, suitable NN architectures were selected and implemented. While we achieved reasonable results in SAR and near-IR simulation using a back-propagation trained multi-layer feed-forward neural network[2], we also developed a unique neural network called Stochastic Associative Memory (SAM)[3] for improved FLIR and SAR simulation. The SAM network not only improved the MSI-to-sensor intensity prediction accuracy for SAR and FLIR but also enabled the learning and prediction, in real time, of an actual sensor's image noise.

The second problem to overcome was the implementation of the MSI neural network processing at real-time video pixel rates. The next section describes how such need for real-time NN implementation was circumvented by using a large look-up table equivalent to a neural network.

NEURAL-NETWORK AND LOOK-UP-TABLE EQUIVALENCE

The underlying concept behind the NNLUT processing is the mathematical equivalence between an M-bit-input, N-bit-output neural network and an M-bit- input, N-bit-output Look-Up Table (LUT).

A very large, 2^M-entry (2^MxN-bit), LUT can contain the transfer function of any associative-memory type neural network architecture having M input bits and N output bits. For example, a 24-bit-input, 8-bit output neural network trained to transform three-channel MSI 24-bit data into 8-bit, 256-level intensity IR image can be implemented by a 24 bit-in, 8-bit-out, 16-Megabyte LUT as shown in Figure 5.

The key to using such a large LUT is to train a neural network on a limited set of exemplar MSI-input / sensor-output pixel combinations and then use the network to compute and define the LUT contents for all possible input/output pixel combinations expected during actual simulation. As shown in Figure 5, the NNLUT approach is practical for sensor image simulation: a total of 24 input LUT bits allows the transformation of three 6-bit MSI chan-

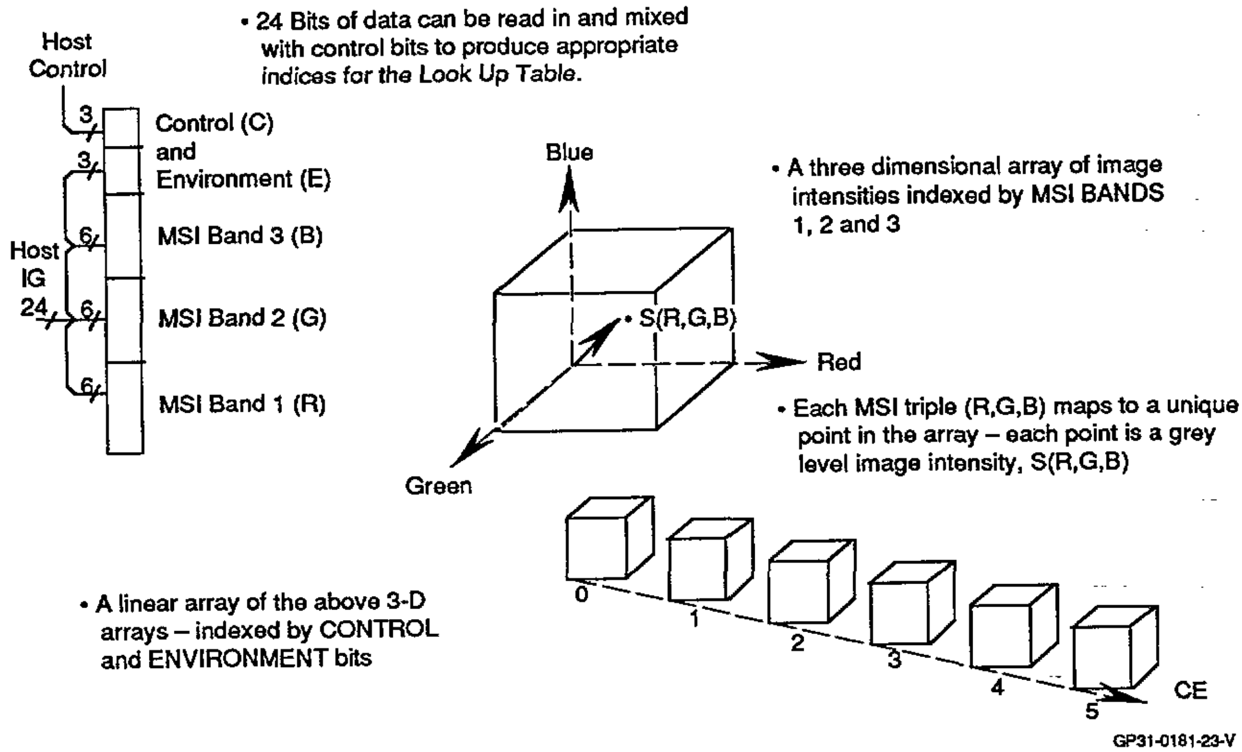


Figure 5. Mapping of MSI and Control Bits Into a Sensor Image Grey Level

nels (18 bits) plus environmental and time-of-day control bits (6 bits). Such capability plays in concert with the need to accommodate several million 12-bit LUT entries for a high-fidelity IR simulation as expressed by IR simulation experts[4,5].

Due to dramatic advances in the availability of high-speed, high-density memory modules, a compact and low-cost hardware implementation of a very large LUT to transform MSI data at real-time video rates has become feasible. Therefore, the requirement to implement a complex NN architecture in hardware executing at real-time video pixel rates for spectral conversion has been eliminated. The next section describes the real-time NNLUT hardware architecture and integration within a sensor simulation system.

REAL-TIME CORRELATED SENSOR SIMULATION SYSTEM ARCHITECTURE

The NNLUT system architecture, represented by the block diagram in Figure 4, integrates with the host IG as shown in Figure 6. To implement simultaneous IR and SAR image simulations, two parallel NNLUT systems can used. The host IG provides MSI images from two channels at independent viewing geometries for transformation by the two NNLUTs.

Architectural Features

A unique feature of the NNLUT system is its capability to process analog RGB color video signals from the host image generator, thus eliminating the need for custom digital video interfacing to a host IG. The host IG effectively encodes the MSI data into an RS-170A color video signal (Figure 6). The NNLUT board(s) are integrated with real-time color image frame grabber and display boards. Using the frame grabber, the NNLUT system digitizes host IG RS-170 RGB color video output into 24 bits. The digital data is passed to the NNLUT boards over a 24-bit digital video bus.

Another feature of the NNLUT system is the *implementation of a real-time pseudo-random number generator* on the NNLUT board to provide SAR real-time statistical texture and coherent noise generation learned by the SAM neural network. In addition, host-selectable LUT input bits can be set or reset, overriding the input MSI data bits, to implement environmentally-dependent simulation control (Figure 5).

For SAR 3-D special effect generation, an image processing accelerator board is included with the

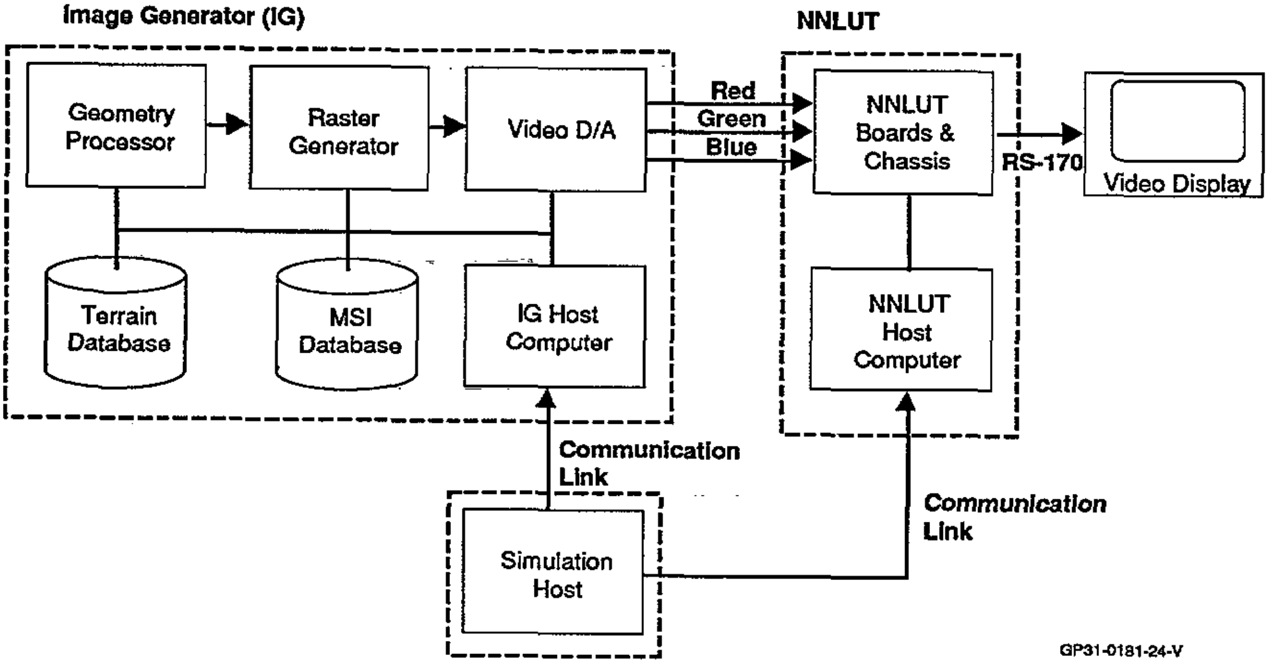


Figure 6. NNLUT System Integration With a Host IG

NNLUT in a single enclosure. Directional edge enhancement and local neighborhood processing performs far-shore brightening and aspecting effects simulation. Therefore, radar 3-D effect generation becomes possible even when high-resolution 3-D terrain elevation data is not available or is difficult to acquire.

NNLUT Implementation

The NNLUT system is currently integrated within an IBM PC/AT-compatible computer and centers around the 4-Megabyte NNLUT board shown in Figure 7. The board can process 22-bit input MSI data into 8-bit output imagery at a continuous real-time video rate of 10 Megapixels, or 30 Megabytes, per second. The 4-Megabyte LUT contents are loaded from the host PC via a 2-Megabyte PC extended memory window.

An ISA (Industry Standard Architecture) PC/AT Input/Output bus chassis allows integration of one or more NNLUT boards. Four boards can provide a complete 24-bit (16.7-million color) input MSI, 8-bit output sensor capability. The NNLUT implementation will accept plug-compatible 2-MByte memory modules for future expansion. Such doubling of the NNLUT size to 8 Megabytes per board will provide 25 MSI-plus-control bit input NNLUT system capability on four boards. The design is further expandable to accommodate 15-nsec speed memory modules for high-resolution video rates of 40 million pixels per second.

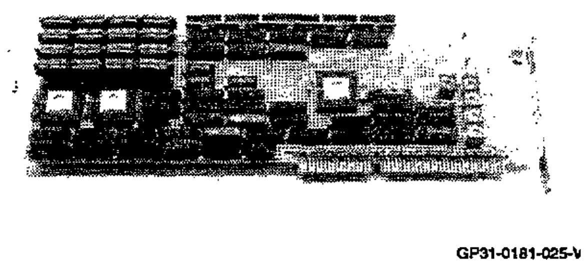
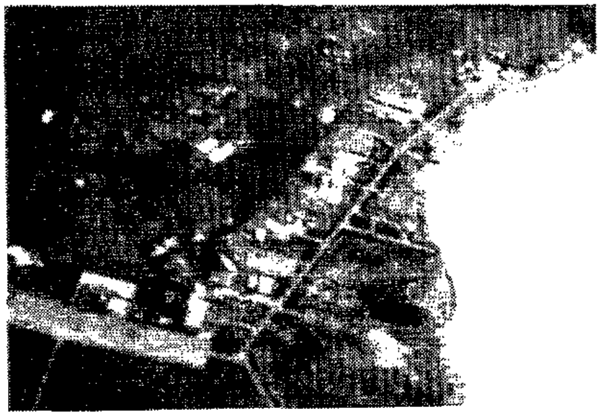


Figure 7. IBM PC/AT – Compatible NNLUT Board

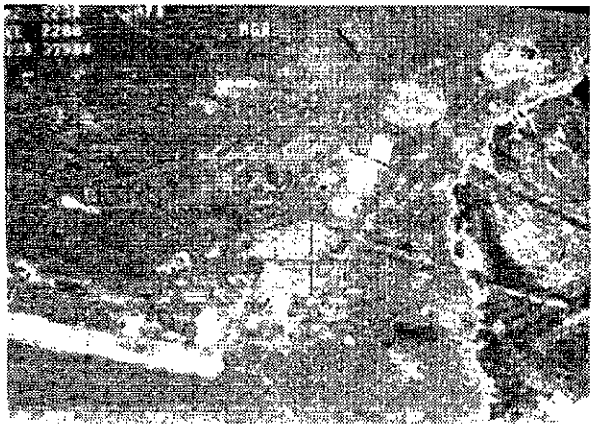
NNLUT IMAGE SIMULATION RESULTS

While live demonstrations best highlight the NNLUT's real-time capabilities, Figures 8 and 9 show samples of simulated sensor imagery generated by the NNLUT system using commercially available MSI data as input.

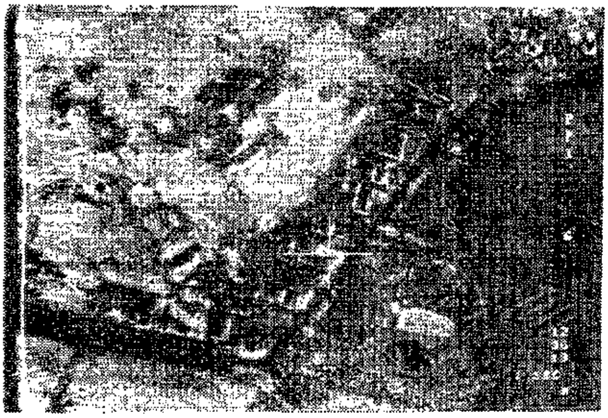
Figure 8(a) shows an overhead-geometry multispectral image of Edwards AFB in California produced by a Flight Safety International VITAL VII texture- capable image generator. The VITAL VII was used due to its ready availability but any



(a) IG-Produced Input Multi-Spectral Image



(b) NNLUT-Simulated IR Image



(c) NNLUT - Simulated SAR Image

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Figure 8. Correlated Image Simulation by the NNLUT System

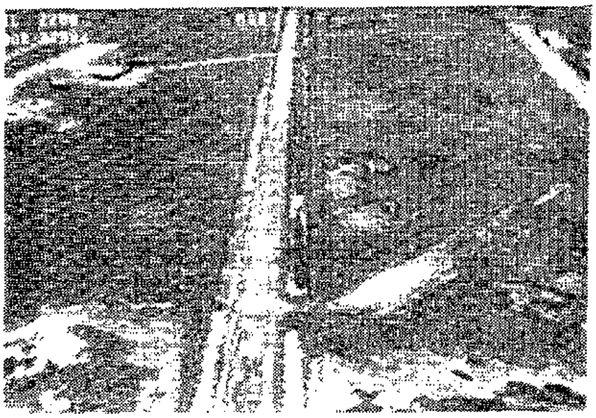

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Figure 9. FLIR Image Simulated by the NNLUT System

texture-capable IG could have been used (See Discussion/System Implementation). The 10-meter per pixel resolution false-color image (shown here in black-and-white only) is a mixture of two 30-meter resolution, 2.1-2.4 micron near-IR, Landsat TM MSI bands sharpened by a 10-meter, panchromatic, SPOT image. Figure 8(b) shows the MSI data transformed by the NNLUT system into an 8-12 micron wavelength IR sensor image. Figure 8(c) shows the same image transformed into an X-band SAR image. Note the high degree of correlation between both simulated scenes and the simulation of directional SAR aspecting effects along the leading edges of buildings. The material- dependent simulated SAR coherent speckle noise learned by the SAM neural network is also evident.

Figure 9 shows a simulated FLIR image as if produced by a narrow field-of-view IR sensor aboard a platform 2,000 ft above ground and at 5 miles range. Note the high degree of geospecific content, or accuracy, in both IR and SAR simulations due to direct processing of geospecific imagery. The building models were manually inserted into the polygonal IG database and MSI intensities were assigned to their sides to match approximate IR heat emission during early evening.

DISCUSSION

System Performance

The NNLUT approach offers a number of desirable characteristics illustrated by the implementation matrix in Figure 10.

	Implementation Component			
Simulation Characteristics	Single IG	Single DB	Direct-From MSI Algorithm/SW	Real-Time Hardware
High Correlation	X	X	X	
High Geo-Specific Accuracy			X	
High Temporal Accuracy		X	X	
Medium Sensor Fidelity	X			X
Rapid Simulation Availability		X	X	X
Real-Time Dynamic Effects			X	X
Compact Enclosure	X	X		X
Low Cost	X	X	X	

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Figure 10. NNLUT Characteristics vs Implementation

A direct consequence of the NNLUT's direct-from-MSI processing is a high degree of real-world geo-specific accuracy in simulated imagery contents. Using the same database for both IR and SAR simulation, the approach also provides a high degree of content correlation for the sensors. And because the simulated imagery can be made available extremely rapidly from the most up-to-date MSI data, the NNLUT can also provide high temporal accuracy. Furthermore, using a single IG host and database for both sensors can result in a very low cost multi-sensor simulation capability.

An issue of importance is the simulated sensor effects fidelity. For IR simulation, the NNLUT system promises dynamic, real-time simulation of diurnal and seasonal variations while IR detector and optics effects are handled by a special post-processor associated with the host image generator and NNLUT. The IR sensor fidelity is therefore potentially high.

For SAR simulation, the sensor fidelity may be estimated to be of "medium" level; 3-D aspecting and far-shore brightening effects are generated without 3-D elevation data. However, an NNLUT approximation of these effects using only MSI data may still be more useful than no simulation at all when high- resolution terrain elevation data is impossible or difficult to obtain, especially over large gaming areas.

While detailed, high-fidelity 3-D SAR effects simulation may be required for some applications, such as training personnel to use real-beam radar systems having a multitude of sensor controls, such fidelity may be an over-kill in many others. For example, in mission planning, preview, and rehearsal applications when automated digital SAR systems with few controls are used by expert systems operators, the SAR simulation provided by the NNLUT should be quite acceptable. Similarly, when large networked battle simulations containing hundreds of sensor-equipped entities are staged, the use of many very low cost but geospecifically accurate and correlated sensor simulations using the NNLUT system would be advantageous.

Looking at the matrix in Figure 10, sensor fidelity is only one of eight desirable characteristics of a total multi-sensor simulation system. While different simulation problems weight the required characteristics differently, in many cases, such as in the large networked scenarios eluded to above, the NNLUT approach can offer a better than "90-percent" solution. And when low cost is the driving factor, the single-IG / single-database NNLUT system can present a very attractive "90-percent" alternative.

System Implementation

The NNLUT system functions as a post-processor of imagery output by a texture-capable IG. Some applications require detailed 3-D effects radar simulation, but many also have a requirement for real-time, highly-correlated IR and radar simulations. Therefore, a careful analysis of the total simulation system performance vs cost trade-offs may reveal that a solution using a single, two-channel, visual host IG and two NNLUT systems is preferrable over using separate, less well correlated IR and radar image generators at higher cost.

Although the NNLUT approach appears to impose a real-time geospecific texture capability requirement on the host IG, the NNLUT could be trained on outputs of any IG with generic or no texture capability. The only requirement is that the

IG be capable of displaying 24 bit color (polygon or texture) derived from MSI data by the database generation system. In fact, this may be a very low-cost alternative for correlated sensor simulation. While under-utilizing the direct-from-MSI sensor simulation capabilities of the NNLUT, the NNLUT could still provide dynamic, real-time diurnal and seasonal IR variations and correlated SAR textures while paving the way for capability improvement when a texture-capable host IG becomes available.

CONCLUSIONS

The development and demonstration of the NNLUT architecture have shown that it is possible and practical to simulate geospecifically accurate and highly correlated IR and SAR imagery directly from MSI data in real time. In fact, both sensor and OTW-visual simulations may be simultaneously possible using only a single IG and three NNLUTs to process a single, common, geospecific MSI plus elevation run-time database. Such a low-cost capability would indeed represent a major advance in image simulation technology.

Potential future enhancements to the existing NNLUT system could include the addition of a real-beam radar scanning display capability, true 3-D radar effects computation from 3-D elevation data, and simulation of dynamic diurnal and environmental sensor effects.

While the NNLUT technology has been developed with mission planning, preview, and rehearsal in mind, the technology may have many uses in civilian applications such as medical imaging, environmental status assessment, and rapid processing of remotely-sensed imagery. One example may be automatic image segmentation and fusion for display of data from magnetic resource images, x-ray machines, ultrasound scanners, and tomography machines. Another may be a special conversion of airborne MSI into SAR imagery for comparing differences in terrain due to flooding or huricane damage. Finally, the NNLUT system has already been successfully applied to real-time, automatic, surface material classification for radar generator database updating using commercially available MSI data.

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REFERENCES

1. Baumann, E. W., and Zvolanek, B., "Sensor Image Simulation Using Neural Networks", IMAGE VI Conference, Scottsdale, Arizona, 14-17 July 1992.

2. Zvolanek, B., and Baumann, E. W., "Rapid-Response Imaging Sensor Simulation", 13th Interservice / Industry Training Systems Conference, Orlando, Florida, 2-4 December 1991.

3. Baumann, E. W., and Williams, D. L., "Stochastic Associative Memory", SPIE Conference on Science of Artificial Neural Networks II, No. 1966, Orlando, Florida, 12-16 April 1993.

4. Crane, P. M., "Forward-Looking Infrared Simulation Fidelity in Aircrew Training Devices", 13th Interservice / Industry Training Systems Conference, Orlando, Florida, 2-4 December 1991.

5. Peters, D. L., "FLIR - A Different World", IMAGE V Conference, Phoenix, Arizona, 19-22 June 1990.