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We have developed an integrated framework for the efficient synthesis of realistic images of three-dimensional terrain with man-made objects and natural clutter. We have shown how many phenomenological aspects of the placement of road networks, tree clusters, populated areas, buildings, etc., can be captured in a computationally-efficient pseudorandom image-generation framework. We generate the underlying terrain with a fast Fourier based procedure. This procedure is seeded with a pseudorandom sequence, so a small number of parameters can characterize a distinctive class of terrain. Within each class, arbitrarily many scenes can be synthesized. We have used procedural definitions for objects; targets or clutter are represented by different models depending on range. For example, at a great distance trees may look like simple cones. But, as the viewpoint nears a tree, finer details will become visible. Procedural definitions also eliminate the need to explicitly store boundary representations for every object placed in the scene. A single procedural definition for an object, such as a tree, can be used at render time by a Z-buffer algorithm to create as many instances as are necessary, with each instance being unique since it uses a unique pseudorandom seed.

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# EFFICIENT GENERATION OF SYNTHETIC TERRAIN IMAGERY FOR AUTOMATIC TARGET RECOGNITION

## FINAL REPORT

A. C. Kak
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1 May 1989 – 30 June 1992

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## OVERVIEW

We have developed an integrated framework for the generation of terrain in three dimensions and for the placement of man-made objects and natural clutter on the terrain. Our main accomplishments are as follows: 1) We have shown how many phenomenological aspects of processes such as the placement of road networks, tree clusters, populated areas, buildings, etc., can be captured in a computationally-efficient pseudorandom image-generation framework. 2) We have shown how placement processes can be integrated with a fast Fourier based procedure for the generation of the underlying terrain. The Fourier based procedure is seeded with a pseudorandom sequence and allows a small number of parameters to characterize different types of terrains and allows for the variation of terrain shape within each terrain type. 3) Our last main accomplishment has been the manner in which we use procedural definitions for objects; our system allows for the generation of scenes in which objects are capable of acquiring different shapes depending on the spatial resolution appropriate to a particular view of the scene. For example, an observer aboard an aircraft may only see triangular forms for trees at a great distance. But, as the craft nears the forest, the observer will begin to see the finer details of the trees. Procedural definitions for objects also eliminates the need to explicitly store the B_reps for every instance of an object placed in the scene. A single procedural definition for an object, such as a tree, can be called upon at render time by a Z-buffer based algorithm to create as many instances of the object necessary, with each instance looking different through the use of a unique pseudorandom seed.

At the time this report is being prepared, an archival journal article is nearing completion. When published, this article[1] will provide an in-depth examination of the issues and will present the methods used in great detail. In this report we will limit ourselves to a presentation of the major results and refer the reader interested in the details to the archival literature.

## RESULTS

Testing classification algorithms for automatic target recognition (ATR) requires data spanning all possible environmental and target conditions. Unfortunately, much testing is now done with data that inadequately characterizes all possibilities because the required data would be very expensive to collect. Moreover, any given data set is specific to the sensor used for the collection of that data and often can not be modified in order to model a different sensor. Therefore, there is a great need for the development of computer graphics tools that would allow the generation of equivalent data in a synthetic manner. It is important that this synthetic data be

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[1] *"Efficient Generation of Synthetic Terrain Imagery"*, by R. L. Cromwell, S. G. Blask, L. L. Grewe, H. Kang, E. Kessler, P. Kisatsky, and A. C. Kak., to be submitted to ACM Transactions on Computer Graphics.

three-dimensional, because, regardless of the sensor used, it must be possible to examine the various features of the data from different viewpoints in 3-D space.

Synthetic generation of imagery for the testing of classification algorithms necessitates two different forms of modeling. On the one hand we need precisely defined geometric models of targets such as tanks and other man-made structures, while on the other hand we need random models of terrain and clutter such as trees, bushes, etc. Modeling of most man-made structures has been well addressed over the years and a number of tools are available for the purpose. However, natural objects such as patches of terrain or trees are more difficult to model. This is because all instances of a particular type of car or tank are identical, whereas no two hills are identical. Natural objects may have similar characteristics, but their specific forms vary widely; consequently they do not easily lend themselves to geometric modeling.

During the last few years, a number of different approaches have evolved for the modeling and rendering of natural objects and scenes. Some of the best known approaches utilize fractals for modeling. A fractal based method may be either deterministic, in which case a primitive element is replaced recursively by a more elaborate pattern, or it may be statistical, where the replacement process is accompanied by a random variation, the result in both cases being striking realism. For a comprehensive review of deterministic fractals, the reader is referred to the book by Barnsley [Bar88]; a discussion on the random variety can be found in [Jef87, PeiSau88]. A most noteworthy feature of fractal-based approaches, especially when they are of the deterministic type, is self-similarity, which means that the patterns produced look similar when examined at different scales – a phenomenon common to many naturally occurring scenes.

While many realistic looking images of natural phenomena have been produced by using random fractals, it is also true that due to the certain frequency domain constraints that must be satisfied by random fractals, they are inherently incapable of simulating phenomena which violate these constraints. To elaborate, for a two-dimensional random process to be called a random fractal (which is the same thing as a fractional Brownian motion), the frequency dependence of its spectral density function must be of the form $f^{-\beta}$ where $2<\beta<4$. However, as was recently demonstrated by Mastin et al. [MasWat87], ocean waves can not be represented by isotropic frequency domain functions of such dependences. To get around this limitation of random fractals, Mastin et al. used empirically obtained frequency domain dependences to synthesize ocean waves from white Gaussian noise. Another modeling contribution where the researchers have been inspired more by the empirically observed phenomenological considerations is reported in [KelMal88]. There the authors have proposed an alternative method that is based on the assumption that stream flow and the accompanying soil erosion are the principal mechanisms for terrain formation. Modeling in [KelMal88] starts with a primitive stream, which may be a straight line, in an already specified patch of flat terrain. A stream junction is then placed on the primitive stream. The location of the junction, the angles of the tributary streams, etc., are based on analytically-derived and empirically-observed factors peculiar to stream flow and soil erosion. The process of replacing a stream by a junction of tributaries is continued recursively until a certain boundary condition on the ratio of the drainage area to the length of the streams generated is satisfied. It is interesting to note that the terrain maps generated in [KelMal88] are not entirely deterministic – meaning that the same underlying stream flow model can lead to different terrains – because the parameters that control the formation of stream networks are dithered by a pseudorandom sequence. This approach is derived from the headward growth models of stream network formation, a subject surveyed by Abrahams [Abr84]. While the [KelMal88] approach is interesting, in the sense that it is capable of generating fairly natural looking maps, it is somewhat limited by the fact that the terrain will be characterized, at least on the average, by one major downslope and the fact that the slopes of sidewalls of all the tributaries will be the same. The generated terrain will be incapable of supporting stationary bodies of water. Also, stream flow is only one of the many different geomorphic processes that shape terrain [Gar74], [ChoSch84]. The problem with simultaneously modeling all erosion phenomena is that we currently lack knowledge of the interactions between them. It is not simply a matter of constructing a model of each process separately and then applying them sequentially, but rather of taking all the processes into account together, something that can not yet be done.

Inspired by the work of [MasWat87] for modeling ocean waves and ocean scenes, in our work we generate the underlying terrain by using frequency spectra derived directly from the USGS maps [USGS90]. Therefore, the two-dimensional random processes that give us the underlying terrain cannot be called random fractals, since in most cases they will not satisfy the $f^{-\beta}$, $2<\beta<4$, constraint in the frequency domain, yet we believe they are a truer depiction of the terrain than what is possible to generate with a purely artificial fractal-based technique.

Although evidently important to the creation of an overall scene, fast terrain generation by the imposition of empirically derived frequency domain constraints is but only one aspect of our modeling system. The other critical aspect of this system is a rule-based framework for the placement of roads, villages, trees, and vehicles. Before laying down, say, roads, this fully automated framework tests the underlying terrain for factors such as drivability, road functionality, the extent of bodies of water along the way, and so forth. This entire object placement framework is itself a random process, in the sense that all decisions regarding the local directions of road segments, the order in which the villages must be connected, etc., are influenced by a random number generator whose output, while random, must conform to certain criteria made necessary by the realism that must exist in the synthesized scene.

Yet another noteworthy feature of our system is that all objects are given procedural definitions. This eliminates the need to store explicitly the boundary representations of all objects in a scene; only the instance-specific parameters need be stored for each object. From these parameters an object is then created at render time. This approach allows dense forests to be created without the burden of having to store explicitly the boundary representations of every limb of every tree.

We have also used procedural definitions for objects to create a multi-resolution capability for scene synthesis. So, if the viewpoint is approaching a wooded area from a great distance, simpler models of the trees would be invoked to create wooded areas. But, as the viewpoint gets closer to the scene, at the render time the simpler models are automatically replaced by higher resolution models. All this can be done from the same terrain scene. In other words, an underlying terrain and a given set of instance-specific parameters for each of the placed objects can give rise to synthesized images using different resolution models.

The Digital Elevation Map, or DEM, is the underlying terrain together with any bodies of water. All models, be they of objects natural or man-made, clutter or target, are placed on the DEM for rendering. We use a frequency domain function, called the Fourier Frequency Magnitude Function (FMF), which may either be specified by a human operator or derived from the elevation maps available from computerized geographical databases [USGS90]. The FMF defines the general shape of the terrain by specifying how much energy is present at all spatial frequencies. The phase of the FMF is randomized to generate a class of similar looking yet distinct terrain maps. For example, our system can produce arbitrarily many examples of mountainous terrain based on the same FMF. While they may look like non-contiguous samples of one mountain range, no two will be identical. In addition to producing as many examples of a given class as desired, this approach can also produce as many distinct classes as needed to model natural scenes. These are important capabilities because they result in economic production of a large number of different scenes necessary for statistically valid testing of ATR algorithms. No longer must a recognition technique be evaluated based on its performance on a small set of samples spanning a narrow domain. After the Fourier based method has given us the underlying terrain, if so desired, bodies of water are created by flooding the terrain, a step accomplished easily by using a threshold elevation as water level and replacing all the flooded terrain pixels by the constant-elevation water pixels. The type of a pixel – at this juncture ground or water – is retained in a separate label map.

We have also devised rules and procedures for the realistic placement of objects such as road networks, villages, trees, etc., on the DEM. Placement of each type of man-made object is governed by rules that take into account the topography of the terrain patch. For example, villages are typically placed in valleys or low-sloping regions of the terrain. For another example, road networks are laid down with the help of a fairly complex set of rules dealing with issues such as inter-village connections, water avoidance, ensuring drivable slopes, etc. These rules were generated by examining a USGS geographical database for selected regions of the United States. Our selection included examples of classes of terrains such as mountains, deserts, plains, etc. These rules utilize both global and local terrain characteristics to produce more realistic scenes. In contrast with man made objects, placement of natural objects, such as trees, is governed by probability distributions that attempt to model the clustering of vegetation caused by factors such as terrain elevation, slope, proximity to water, and terrain type.

We use a z-buffer based rendering procedure which allows us to incorporate pertinent illumination models and makes it possible to use procedural definitions for objects. Strictly speaking, specification of illumination models requires that the material properties of the different surfaces be specified in terms of their reflection, emissivity, and transmissivity coefficients. While we realize that much sensor modeling can be affected by appropriate specification of these coefficients, for work to date we have assumed surfaces to be diffuse reflectors and have used simple Gouraud shading to compute the color of object surfaces as illuminated by point light sources. Gouraud shading is a method for the interpolation of color at the interior point of a facet given the color at the vertices of the facet. Initial results are promising, and more complex material modeling should further increase the realism of generated scenes.

At the end of this report we have included some of the images produced by our system.

## PARTICIPATING SCIENTIFIC PERSONNEL

Avi. C. Kak (principal investigator), Robert L. Cromwell (earned Ph.D. in May 1992), Steven G. Blask, Lynne L. Grewe, and HoSeok Kang.

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