Modeling Camouflage Screens Using Xpatch

by
E.L. Jacobs
CECOM RDEC
Night Vision Electronics Sensors Directorate
Visionics, Modeling, and Simulation Division
Ft. Belvoir, VA 22060-5806

ABSTRACT

The radar performance of a camouflage screen is dependent upon five parameters; deployment, context, material reflectivity, reflectivity pattern, and surface roughness. A geometric model of draped camouflage screens has been produced which allows arbitrary variation of these three parameters. The model uses a spring connected point mass description of the net. Draping is accomplished via a constrained minimization of the total energy in the structure using a modification of the simulated annealing technique. Constraints include corners staked to a flat ground and support poles. This geometric model was converted to a facet representation and used with the Xpatch electromagnetic prediction code to produce synthetic aperture radar (SAR) images of a screen over a simple target in a statistically homogeneous background. The material in the screen was modeled as a resistive sheet. Arbitrary reflectivity patterns with N resistivities were achieved through the use of an N state Markov process. Roughness was achieved by perturbing the vertices of the facets in the geometric model. Qualitative comparisons of Xpatch SAR imagery and real SAR imagery indicate that all major scattering and attenuation effects of camouflage screens are accounted for by this approach.

INTRODUCTION

The work described in this paper represents a recent effort by NVESD to improve the way radar camouflage screens are designed. There is nothing new or novel in this work since most of the pieces have been developed by others. However, the application in the fashion about to be described represents a significant enhancement to the design process for camouflage screens.

As a prelude to the work here, a brief introduction to camouflage screen technology will be given, followed by a discussion of what makes a good camouflage screen. The modeling approach used for this work will then be described with results from Xpatch and conclusions following.

CAMOUFLAGE SCREEN DESIGN

A camouflage screen is composed of two structures: the base, or net, and the garnish. The net is woven from a strong yarn and the size of the weave can vary from several centimeters to a few millimeters. The garnish is composed of an incised, lightweight fabric, sometimes coated in plastic, which is attached to the net. Either the net or the garnish can be made of conductive material but usually only one of these components has any electromagnetic significance.

Due to weight requirements, the electromagnetically significant portions of camouflage screens have traditionally been made with conductive fabrics that are thin with respect to the wavelength of most radars. Modern fabrication techniques allow the conductivity of these materials to be set arbitrarily. For the purposes of analysis and simulation, these materials function as resistive sheets. A resistive sheet is similar to a planar dielectric half space in that the reflection and transmission coefficients differ by a constant. The resistive sheet differs from the dielectric half space in that there is no refraction through the material.

Camouflage screens are normally not applied directly to a target but are supported above a target by a series of spreaders attached to poles with the corners of the screen staked to the ground. Placement of the poles is done in a manner such that the screen structure looks "natural". This usually results in the deployed screen having a dome like shape.

Now that some general notion of the electromagnetic structure of a camouflage screen has been established, it would be desirable to know how the parameters of the structure can be manipulated for optimal radar camouflage performance. Operationally, a camouflage screen will be optimal if it can match the background and conceal the target. The most obvious way to determine how well a candidate screen meets this criterion is to conduct operational field tests. However, the small budgets of camouflage development programs rule out extensive field testing.

Currently, candidate screens are compared in the laboratory against a standard of sorts: the US Army Lightweight Camouflage Screening System (LCSS). An overview of current laboratory test procedures is given in [1]. The LCSS was developed during the seventies using purely empirical methods and extensive field testing [2]. It has shown good success addressing the optimality criteria mentioned previously with respect to radar bands but has deficiencies in other sensor bands. Therefore, new designs are being considered.

Recently, the Army briefed several camouflage manufacturers on what was understood to be the crucial parameters necessary to make an effective radar camouflage screen. Each manufacturer produced a prototype which was tested in the field along with the LCSS. The image shown in Figure 1 is a mosaic of Synthetic Aperture Radar (SAR) images showing the results from three of the candidate screens and the LCSS. Each screen has an "L" shaped array of omnidirectional corner reflectors under it. The radar was operating at Ku band and had a nominal resolution of one foot.

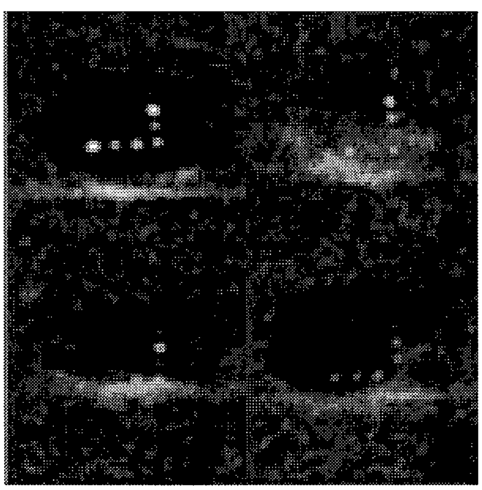

Figure 1. SAR images of camouflage screens.

Interestingly, these camouflage screens are essentially identical in laboratory response but are obviously very different in performance. In fact, informal observer tests indicate that the screen in the upper right quadrant is superior in performance to the others. This is fortunate since it is the screen in current use: the LCSS.

From the previous image and others like it, three main conclusions can be drawn. First, the laboratory procedure used to evaluate camouflage screens is deficient in that it is not predictive of field performance. The Camouflage, Concealment, and Deception branch at NVESD is currently addressing this deficiency. Secondly, there is a gap in our knowledge of the key parameters that influence radar camouflage performance. As mentioned previously, the manufacturers were told everything that was currently understood to be essential in designing effective radar camouflage. Laboratory tests indicate that they were effective in incorporating that knowledge in their designs. Thirdly, image based analysis is a powerful tool for analyzing the performance of radar camouflage screens. Although diagnostic information of the type available from laboratory tests is not obtained, a glance at an image allows an observer to quickly assess the performance of a camouflage screen.

For the camouflage designer, the second conclusion is most important. Faced with high field test costs and small budgets, a model-based approach to identifying the key design parameters is needed.

MODELING CAMOUFLAGE SCREENS

Experience and imagery like that shown in Figure 1 suggest that a successful modeling approach will incorporate three features: namely, accurate geometry and materials models, realistic contexts, and image-based metrics for evaluation.

The work presented here will highlight the first two of these features. An example of image based analysis will also be given in the results.

As a prelude to the current work, an examination of prior efforts at camouflage screen modeling was initiated. A very practical and intuitively satisfying model of camouflage performance was introduced in 1985 by Dan Hunt [3] of the White Sands Missile Range. Hunt's model allows the prediction of the signature of a target based on the signature of the uncamouflaged target and measured responses from the camouflage screen. The model ignored phase effects but was in good agreement with measured results.

A more rigorous approach was attempted in 1989 by Bruce MacLeod [4], then a masters student at the Air Force Institute of Technology. The model assumed that the camouflage screen formed a layer of effective media and the resulting dielectric constants of the layer were used to predict the response of a target covered by a camouflage screen.

In 1990, Dennis Blejer [5] of MIT Lincoln Labs modified Hunt's model so that it took into consideration phase effects and used it to predict the SAR signature of targets with camouflage.

In 1993, Jacobs and Dumouchelle [6] developed a set of analytic expressions based on the Kirchoff approximation for the parameters used in the Hunt model based on the resistivity and roughness of the camouflage screen.

In 1994, Keydel et. al. [7] incorporated Blejer's modification of Hunt into an integrated modeling and prediction package known as RADSIM-GTM. A model for draping a camouflage screen was also incorporated into the model.

The success of some of the prior efforts (especially [7]) indicate that good models for deployment and realistic contexts will give results most like those obtained from field trials. A deficiency of the prior efforts is that the structure and electromagnetic properties of the materials are defined too abstractly; the description of the screen used in the models cannot be directly related to the fabrication of the cloth used in the screen. At a minimum, performance of the screen must be related to the reflectivity and surface roughness characteristics of the screen materials since these parameters can be directly manipulated by the manufacturer. For camouflage design, a useful model will then incorporate deployment, context, reflectivity, pattern, and roughness.

Modeling of fabric draping is a highly non-linear problem that has been addressed both by textile scientists and computer graphics researchers. In general, there are three schools of thought on how it should be done. First there is the technique of forcing the fabric to follow the well known catenary curve between constraint points and then initiating a relaxation process that gives the resulting structure a more "cloth like" appearance. This technique was developed by Weil [8] at AT&T Bell Laboratories in 1986. A second, and more rigorous, technique that has been put forward is the use of elastic shell theory to model fabric. The fabric is modeled as a topologically 2D grid of 3D points and equations for the energy in the shell are derived as a function of the grid points. Feynman [9] at MIT introduced this approach in 1986. The third technique that has been advanced in the literature is modeling the fabric as a collection of point masses and springs. Haumann and Parent [10] introduced software using this approach in 1988. Two of these techniques have been successfully applied to the draping of camouflage screens. Keydel [7] introduced a net draping model based on the catenary curve technique while Loyd [11] has modeled the screen as point masses and springs. Coincidentally, both of these papers were presented at the 1994 Ground Target Modeling and Validation Conference.

For the work being presented, the procedure outlined in Loyd's paper was used. A brief review of Loyd's procedure along with the relevant equations will be given. The interested reader should refer to [11] for more details.

A mechanical model for a screen is formed by assuming the screen is made up of point masses, equidistant from one another, and connected to their six neighboring masses by massless springs. The springs are ideal and do not support compression.

After the structure has been described, draping is accomplished by a three step process. First the springs and masses are all placed in some rest state. The point masses that are associated with poles and stakes are then forced to their final desired resting place. Then, the remaining free masses are moved in some fashion until the total energy in the screen structure is minimized. The difficult point in this procedure is defining a reasonable mechanism for moving the nodes that allows the screen to robustly achieve minimum energy.

The total energy in the screen structure is given by the following equation.

$$E = \sum_{n}^{all} g m_n z_n + \frac{1}{2}\sum_{s}^{all} (k_s \max(d_s - d_0, 0))^2 \quad (1)$$

In the equation above, g represents the gravitational acceleration constant, m_n is the mass of the n^{th} node, z_n is the height of the n^{th} node, k_s is the spring constant of the s^{th} spring, d_s is the current length of the s^{th} spring, and d_0 is the rest length of a spring. The symbols n and s represent indices over the nodes and springs respectively. Note that the first term corresponds to the gravitational potential energy of all the point masses while the second term is associated with the energy bound up in all the springs.

Minimization algorithms that use gradient information are in general faster than those that do not use gradients. Therefore, knowing the gradient of the quantity to be minimized is advantageous. For the problem at hand, the gradient of the energy is just the force on a node which is given by the following equation.

$$\underline{F}_n = gm_n\hat{\underline{z}} + \sum_j^{neighbors} -k_{nj}\ \max(\|\underline{D}_{nj}\| - d_0, 0)\frac{\underline{D}_{nj}}{\|\underline{D}_{nj}\|} \quad (2)$$

In (2), the subscript n is the index of the node whereas the subscript j is taken over the neighboring nodes to node n. The vector $\underline{D}_{nj}$ is the vector drawn from node n to node j. As with the energy equation, the first term in the equation corresponds to the gravitational force on the node while the second term is the vector sum of the spring forces.

Loyd used the Conjugate Gradient method to minimize the energy in the screen structure. He noted that occasionally, the screen would get "stuck" in non-minimal energy states, and that this could be remedied by periodically introducing a random "shake" in the nodes. Randomly "shaking" the structure does relieve this behavior but it was found that the size of the "shake" has to be changed as the structure approached minimum energy. The resulting algorithm is described as Modified Simulated Annealing. The nodes are moved along the conjugate gradient direction but the distance moved is random; governed by the annealing schedule of the simulated annealing algorithm.Another difference between the current work and Loyd's work is that the boundary nodes associated with poles or spreaders are fixed. The material is not allowed to slip over them.

After the draping procedure is completed, the resulting node/spring configuration is converted into an Xpatch facet file. Figure 2 shows a sequence of images depicting various stages in the net draping process.

As mentioned earlier, the materials in camouflage screens are well represented as resistive sheets. The Fresnel reflection and transmission coefficients for a resistive sheet are given by the following equations for vertically polarized incident wave

$$\Gamma = \frac{-\eta_0}{\eta_0 + 2R\cos\theta} \qquad (3a)$$

$$T = \frac{2R\cos\theta}{\eta_0 + 2R\cos\theta} \qquad (3b)$$

and by

$$\Gamma = \frac{\eta_0\cos\theta}{\eta_0\cos\theta + 2R} \qquad (4a)$$

$$T = \frac{2R}{\eta_0\cos\theta + 2R} \qquad (4b)$$

for a horizontally polarized incident wave. These allow the user to compute inputs necessary for Xpatch runs. Note that θ in the equations above represents the local angle of incidence. R is the resistivity of the sheet and η_0 is the impedance of free space.

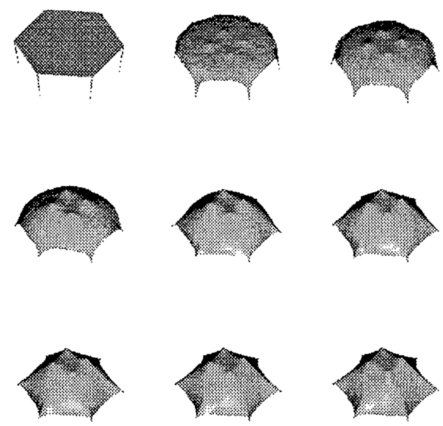

Figure 2. Draping of a camouflage screen.

The definition of reflectivity and transmissivity given previously must be related to the structure of the screen in order for the effect of patterning to be modeled. This involves simply adding a number representing the type of material to the facet descriptions in the Xpatch facet file. Xpatch will then modify its calculations as appropriate for the material encountered in each facet of the structure. To produce the patterns used in this work, the screen was assumed to be made up of N different materials where N is an arbitrary integer less than the number of facets in the structure. A facet was then chosen at random and a material designation (1 to N) is randomly assigned. An adjacent facet was then chosen and its material assigned based on a user specified N dimensional probability matrix. This procedure was repeated until all facets had been assigned a material designation. This process of assigning a material to a facet represents an N state Markov process. Figure 3 shows the results of the process for a binary screen with one of the materials rendered transparent.

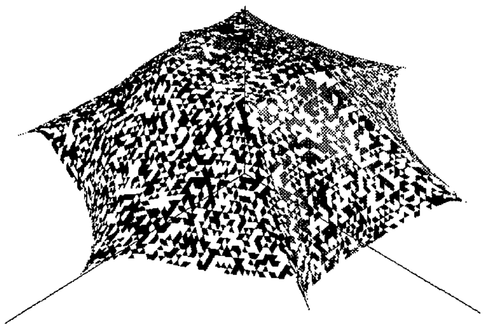

Figure 3. Reflectivity pattern in a camouflage screen.

Another property to be incorporated in the model is surface roughness. The surface properties of camouflage screens, with regard to small scale (on the order of a wavelength) roughness, are unknown. In the absence hard data on the nature of the roughness in the screen, a simple procedure was used to simulate roughness. With the center of mass of the screen aligned with the origin, a vector is formed using the origin and one of the vertices of a facet chosen at random. A random length drawn from a zero mean uniform distribution is then added to the length of the vector. The variance of the uniform distribution is set by the user. This process is repeated for all vertices in the structure. The result is the "bumpy" camouflage screen shown in Figure 4.

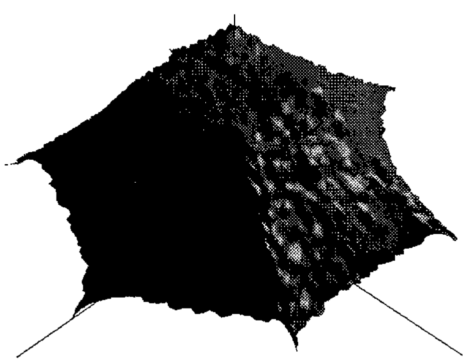

Figure 4. Surface roughness added to a camouflage screen.

Realistic contexts for camouflage screens can be quite complex. For the purposes of this study, a simple circular Gaussian noise model was chosen. To enhance the realism of the model, the first order statistics of the Gaussians were set so that the resulting noise field had statistics similar to the measured results reported in Ulaby and Dobson [12]. Although the simple model used here may be inadequate for some simulations, it should be pointed out that any scene available as a complex image can be used as a background.

The time domain version of Xpatch, Xpatcht, provides a utility for generating a mask file. The mask file is an image composed of three values; 0,1, and 2. The value 0 is written in regions where the target has no effect on the background. The value 1 is written in regions where the target is directly covering the background. The value 2 is written in regions where the target is shadowing the background. If the target to be added is impenetrable, the data in the mask file is used to zero all covered and shadowed regions in the background. The target response is then coherently added to the background response. Since there is significant transmission through a camouflage screen, a different method of adding in the target response is necessary. A simple signal model, similar to that proposed by Hunt, was used to place the target in the background. By this model, the response in a region affected by the target is simply the response of the target plus an attenuated version of the background. For covered regions, an incident wave must pass through the screen twice before returning to the receiver. Therefore, the attenuation in covered regions is assumed to be the two way average transmission loss of the camouflage screen. For areas shadowed by the screen, it is the four way average transmission loss since the incident wave must traverse two sections of screen.

RESULTS

Using the previously described methods, a geometry file for a camouflage screen was produced. A 2 foot, square, dihedral corner reflector was placed under the screen. The image in Figure 5a shows a SAR image produced using the frequency domain version of Xpatch . Figure 5b shows a SAR image produced using the time domain version of Xpatch . In both Xpatch results, a uniform weighting function was used during image formation. To allow faster run times, while maintaining the small scale features found in real camouflage screens, the model was only 5 meters in extent and used a maximum of 9200 facets. The screen used in the real SAR image was approximately 10 meters wide.

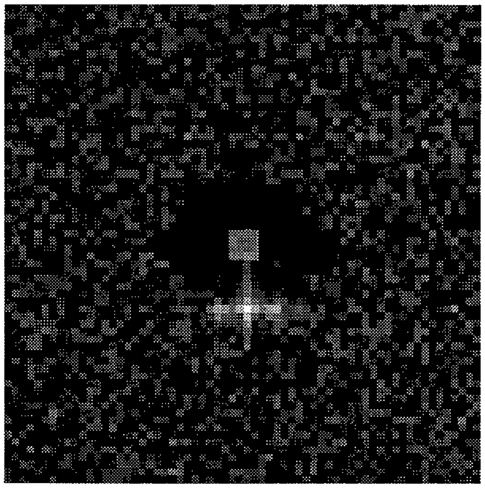

Figure 5a. SAR image of camouflage screen formed using Xpatchf.

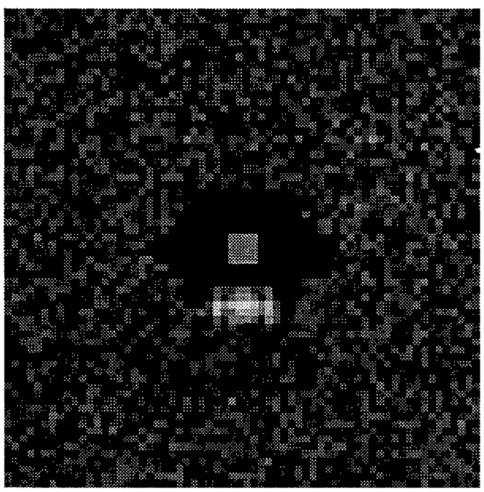

Figure 5b. SAR image of camouflage screen formed using Xpatcht.

Although no quantitative measures are applicable, qualitatively the images in Figures 5 are in close agreement with the images in Figure 1. All show specular flash, background attenuation, and target attenuation. There is an azimuthal spread in the specular flash of the real screen that is not reproduced in the simulated imagery. It has been speculated that the cause of this spread in the real image is motion of the screen. Since no motion was modeled in the simulation, it is reasonable to expect this effect to be missing in the simulated data. Although the Xpatchf results are more exact with respect to materials and image formation, Xpatcht results are obtained much quicker and, at least qualitatively, do not suffer much from the approximations used in obtaining them.

Figure 6 is a mosaic of simulated SAR images of camouflage screens illustrating how the performance depends on pattern and roughness. Pattern is varied along the columns with the left hand column having no pattern, the middle column having a small scale pattern (holes on the order of a 4 inches) and the right hand column having a large scale pattern (holes on the order of 10 inches). Roughness is varied along the rows with the bottom row having no roughness, the middle row having 4 inches of roughness, and the top row having 8 inches of roughness.

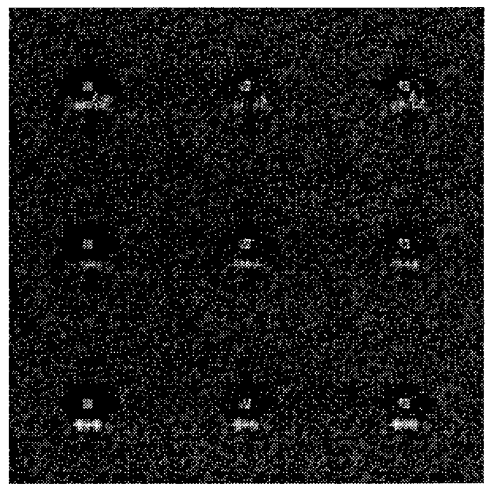

Figure 6. Mosaic of SAR images of camouflage screens.

Table 1 shows a ranking of the images based on an informal perception experiment using 11 observers. The rankings are from 1 to 9 with 1 being the "worst" camouflaged and 9 being the "best". These results indicate that a small scale pattern is better than no pattern or a large scale pattern and that performance is increasing as roughness increases. These results show the power of a simulation combined with an image based analysis in providing specific design information. Twenty years ago, such results could not have been achieved without incurring substantial costs.

TABLE 1. Ranking of Camouflage Screens in Figure 6.

4	9	8
2	6	7
1	5	3

CONCLUSIONS

In conclusion, a methodology for using Xpatch to produce realistic simulated SAR images of camouflage screens has been described. This methodology is detailed enough to at least qualitatively capture all important scattering phenomena associated with camouflage screens. Quantitative validation of the result presented here will require a better set of field data and ground truth. Using this methodology and Xpatch, results for a wide variety of reflectivity, pattern, and surface roughness can be produced quickly. These images can then be used in observer experiments to place quantitative values on the relative performance of the designs. This capability will greatly benefit the design of radar camouflage.

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