Project Summary for ARO MURI Topic #28

"Model Classes, Approximation, and Metrics for
Dynamic Processing of Urban Terrain Data"

Terrain models are a rich resource to both military and civilian sectors including such applications as autonomous navigation, mission planning, battlefield assessment, and emergency preparedness. Their usefulness depends on succinct encoding of terrain data not only for fast query and retrieval but also for efficient and accurate transmission of this data over restricted communication channels. Some applications demand real-time conversion of point cloud data to a continuous terrain representation.

Unfortunately, the development of processing tools for terrain surfaces has been ad hoc and too often simply borrowed from image processing. Terrain maps are not conventional images and most image processing tools fail to extract the essential geometry and topology in terrains and fail to adhere to particular demands in the typical terrain application settings. While newer terrain modeling algorithms are meeting some success in capturing and prioritizing geometry through techniques from differential geometry, they fail to capture high order topology because they treat terrains as functional surfaces. This is particularly damaging in urban terrain where man-made structures such as overhangs, bridges, arches, towers, and light poles, are not captured correctly. In addition, the metrics used to make decisions on bit allocation and accuracy of fit do not always match well with the targeted applications. Meeting these application demands requires substantially new metrics to measure distortion and new representation systems (explicit/implicit) that capture topology and geometry of surfaces. Implicit representations provide a simple way to capture higher genus topology, significantly reduce the number of bits needed to encode terrain (especially in urban settings), and allow for fast assimilation of line-of-sight and no-fly regions for navigation.

It is our contention that the advances necessary to obtain terrain models that accurately capture geometry and topology in application-driven metrics will require an integrated effort between scientists who specialize in mathematical modeling and practitioners who apply terrain modeling to specific application domains. Accordingly, **Ronald DeVore (PI)** of **The University of South Carolina** has organized a compact team of world class researchers in mathematics, engineering, and computer science to address the full spectrum of dynamic 3D modeling problems of urban terrain data. In addition to South Carolina, the participating universities include **UCLA**, **Virginia Tech**, **UC-Irvine**, **Texas**, **Texas A&M**, **Princeton**, and **Rice** and are requesting an annual funding level of **$1,000,000**, totaling $3 mln for the Base 3 years, $2 mln for the Optional 2 yr period, and $5 mln total.

We propose a comprehensive development of both theory and algorithms which specifically addresses the deficiencies in terrain processing. The theory will analyze the expected performance of hybrid methods based on explicit and implicit representations including a rate distortion theory for Hausdorff and Line of Sight associated metrics. We propose to capture inherent geometry and topology in terrains by using both implicit and explicit representations of terrain integrated seamlessly into a terrain encoder. The encoder will be designed to work either directly from raw point cloud data or processed structured data. Our development will be carried out in the context of application domains including Autonomous Navigation and Line of Sight with on-line implementation on software and hardware platforms which are validated at the team's experimentation facilities.

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"Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data"

Ronald A. DeVore, PI

ARO MURI Topic BAA06 #28

1 Statement of Work

Terrain models are a rich resource to both military and civilian sectors including such applications as autonomous navigation, mission planning, battlefield assessment, and emergency preparedness. Their usefulness depends on succinct encoding of terrain data not only for fast query and retrieval but also for efficient and accurate transmission of this data over restricted communication channels. Some applications demand real time conversion of point cloud data to a continuous terrain representation.

Unfortunately, the development of processing tools for terrain surfaces has been ad hoc and often simply borrowed from image processing. Terrain maps are not conventional images and most image processing tools fail to extract the essential geometry and topology in terrains and fail to adhere to particular demands in the typical terrain application settings. While newer terrain modeling algorithms are meeting some success in capturing and prioritizing geometry through techniques from differential geometry, they fail to capture high order topology because they treat terrains as functional surfaces. This is particularly damaging in urban terrain where man-made structures such as overhangs, bridges, arches, towers, and light poles, are not captured correctly. In addition, the metrics used to make decisions on bit allocation and accuracy of fit do not always match well with the targeted applications.

Meeting application demands requires a new foundation for terrain modeling that includes substantially new metrics to measure distortion and new representation systems that capture topology and geometry. These new representation systems must include implicit representations of surfaces. Implicit representations provide a simple way to capture higher genus topology, reduce the number of bits needed to encode terrain (especially in urban settings), and allow for fast assimilation of line of sight and no-fly regions for navigation. The significant advances required to properly address the inherent complexity of terrain modeling will not be met through ad hoc and incremental studies. Rather, it will require the development of a comprehensive mathematical theory with commensurate algorithms.

This project will develop both theory and algorithms which specifically addresses the deficiencies in terrain processing. The theory will analyze the expected performance of hybrid methods based on explicit and implicit representations including a rate distortion theory for Hausdorff and Line of Sight associated metrics. The inherent geometry and topology in terrains will be captured by using both implicit and explicit representations of terrain integrated seamlessly into a terrain encoder. The encoder will be designed to work either directly from raw point cloud data or processed structured data. Our development will be carried out in the context of application domains including autonomous navigation and Line of Sight. The algorithms will be implemented in a software and hardware platform that will be validated at an experimentation facility.

Our theory will include

- a mathematical description (model classes) of which surfaces correspond to terrain,

- a determination of which metrics are most suitable to guarantee preservation of the essential geometry and topology of terrain,
- a rate-distortion theory for these model classes with respect to these metrics,
- an identification of fundamental explicit and implicit building blocks for the model classes which will sparsely represent the geometry and topology of terrain surfaces.

Our algorithmic development will address the

- the assembly of these building blocks through constrained optimization to guarantee geometric and topological fidelity,
- building fast algorithms to extract these building blocks from both structured and point cloud data,
- building fast algorithms to encode and decode the sparse decompositions,
- fusing information gathered from multiple sensors.

The models for terrain surfaces will seamlessly incorporate both explicit and implicit representations, exploiting the advantages of both of these viewpoints while minimizing their drawbacks. Explicit representations are efficient, easy to extract and encode. However, implicit methods can treat geometry and topology more effectively, and align more comfortably with Line of Sight applications. A hybrid method will most likely provide the ultimate solution. The rate distortion theory will include the analogue of Kolmogorov entropy for mathematical function classes and the Shannon entropy for stochastic encoding. Once the limits of rate distortion are understood, the development of encoders that perform near the optimal limits should be realizable. Such encoders will integrate both explicit and implicit methods for optimal performance. Nonlinear and anisotropic numerical methods will be at the core of such a development. The representation systems for terrain models will allow for the treatment of both structured and point cloud data. The development of such a comprehensive theory can then drive the development of commensurate algorithms and software. All of this will be made with a careful eye to the demands of applications.

The advances necessary to obtain terrain models that accurately capture geometry and topology in application-driven metrics will require an integrated effort between scientists who specialize in mathematical modeling and practitioners who apply terrain modeling to specific application domains. We have accordingly assembled a group of world class researchers in mathematical analysis, geometry, engineering, and computer science to address the full spectrum of terrain modeling problems. Their expertise not only spans these disciplines but has extensive experience with terrain surfaces. The research strengths of these scientists reinforce and complement one another.

Professor Ronald DeVore is the world's leading figure in approximation and its application to image/signal processing and numerical methods and will be the Scientific Lead on this project. He is a member of the American Academy of Arts and Sciences. As Director of the Industrial Mathematics Institute (IMI) at the University of South Carolina, he has led the development of the IMI terrain encoder. His colleagues, Professors Robert Sharpley and Peter Binev, will be integral parts of this effort. Professor DeVore will be responsible for the overall research coordination of the project. He will also lead the effort to develop a mathematical theory for terrain encoding including the model classes and rate distortion.

Professor Stan Osher (UCLA) is reknown for his development of essentially nonoscillatory (ENO) methods, level set methods and total variation diminishing numerical methods which have already had a dramatic impact on image denoising, registration, and inpainting and are currently being developed for the processing of terrain data. Osher is a member of the National Academy of Sciences and has received numerous awards for his research. He is also Director of Special Projects at UCLA's NSF-funded Institute for Pure and Applied Mathematics. Professor Osher will provide major senior leadership to the project. He will lead the effort to incorporate implicit representations into terrain modeling including compression and denoising of both urban and natural terrains. This effort will also improve on the recently developed line-of-sight and path planning algorithms. He will be responsible for coordinating the efforts of UCLA, Texas, and UC Irvine.

Professor Richard Baraniuk (Rice University) is an expert in image processing, hidden markov methods, multiscale methods for geometric analysis for higher-dimensional signal processing, and compressed sensing. He will collaborate closely with South Carolina to develop new theory and algorithms to extract three-dimensional geometry information from multiple images of a scene. Emphasis will be placed on manifold methods and shape-from-motion methods. Images of multiple modalities will also be explored. Tree-based encoders will be developed for geometrical data described by meshes.

Professor Andrew Kurdila (VT) currently serves as the PI of the JOUSTER program at Virginia Tech and is an expert in dynamical systems and control theory with extensive experience in multiresolution and wavelets. His role will be to coordinate software programming, hardware integration and validation though the extensive JOUSTER facilities. He has previously served as the scientific lead on a multi-university AFOSR research project entitled "Vision-Based Control of Agile, Autonomous Micro Air Vehicles and Small UAVs in Urban Environment" which resulted in major advances in autonomous flight by vision and mathematical learning. His colleagues, Professors Mark Pierson and Michael Roan, will have major roles in this effort to include multi-sensor data fusion. Professor Kurdila will coordinate the efforts of Virginia Tech and Princeton.

Professor Sanjeev Kulkarni (Princeton University) is a recognized expert studying pattern recognition and learning theory. The extension of the interplay between learning theory and approximation theory will be carried out in this proposal for multiple input sources and distributed computing.

Professor Guergana Petrova (Texas A& M University) has been one of the innovators of anisotropic models for surfaces and their compression using multiscale methods and is at the forefront of the development of numerical methods for evolution equations. Professor Petrova will address issues necessary in obtaining terrain models that accurately capture geometry and topology in application driven metrics. The theory will classify surfaces in terms of how well they can be approximated in the Hausdorff metric, namely she will participate in the development of a rate-distortion theory for the compression of surfaces.

Professor Yen-Hsi Richard Tsai (University of Texas) is a leading figure in dynamic visibility and level set methods. His awards include an Alfred P. Sloan Fellowship and the FEMLAB prize. Professor Hongkai Zhao (UC, Irvine) is an expert on implicit representation of surfaces and level set methods and is also a Sloan Fellow. Professors Tsai and Zhao will work closely with Professor Osher on integrating their work on implicit representations towards the extraction of implicit representations of surfaces from structured and point cloud data in noisy environments.

2 Technical Approach

While it is now well recognized that terrain modeling is a critical component of many civilian and defense application domains, this realization has unfortunately not yet resulted in a platform for terrain processing which meets the demands of these applications. This state of affairs has occurred for several reasons. Foremost among these was the belief that terrain processing could be simply handled by borrowing tools from image processing. Terrain maps are not conventional images and most image processing tools fail to extract the essential geometry and topology in terrains and fail to adhere to particular demands in the typical terrain application settings.

Deficiencies of present day terrain processing platforms occur in the following areas.

2.1 Metrics

Metrics are used to measure the distortion between the actual terrain and what is computed or encoded. In encoding, the metric determines how to allocate bits since the goal is to minimize distortion in the chosen metric. It is therefore important that the metric matches the application domain. In navigation, it should accurately describe fly and no-fly zones. The default least squares metric, dominant in image processing, is not suitable for terrain map applications. For example, the least squares metric does not sufficiently penalize long thin structures such as wires and light towers and over penalizes broad areas with very small undulations. Some of the more recent encoders (see for example [31]) have recognized this and replaced the least squares metric with the maximum norm in encoding terrains. However, the max-norm, like all function norm metrics, is also not satisfactory since it is coordinate biased. It severely penalizes any distortion in the vertical direction. A more suitable metric for terrain encoding and intended application domains is the Hausdorff metric which applies equally well to arbitrary surfaces (not necessarily graphs of functions). In other applications, the Line of Sight (LOS) is the dominant criteria and distortion in LOS should be the primary criteria in encoding. While the Hausdorff metric does better in preserving LOS than the other known metrics (see [32]) one should be able to do more efficient encoding if one works directly with preserving LOS instead of going through the Hausdorff metric.

2.2 Topology

Terrains are not necessarily graphs of functions. This is particularly apparent in urban terrain (bridges, guy wires, towers, and other man-made structures) and occurs in natural terrain as well (caves and overhangs). Often this topology is exactly what we wish to capture in an application. For example, in navigation, the failure to capture this topology will incorrectly label holes as no-fly zones when they may be precisely the preferred navigational path. Capturing this topology necessitates a departure from viewing terrain as functional surfaces. New techniques are needed for extracting and prioritizing this topology, as are new systems for representing terrain in terms of fundamental building blocks.

2.3 Geometry

Natural terrain has inherent geometry described by level curves, ridge curves, drainage curves, critical points and monotone regions. Any encoding should extract, prioritize, and preserve this geometry. While state-of-the-art terrain encoders currently do precisely that (see [31], [32]), they are deficient in at least two ways.

First, man-made terrain, dominant in urban environments, typically has simplified geometry. Hence, it should be possible to represent these portions of the terrain efficiently and to encode them with very few bits. The extraction of man-made structures such as building, towers, poles, and wires is important in most applications. Their proper labelling and encoding will also reduce the computational budget in post analysis. Current encoders do not seamlessly extract, prioritize and encode this geometry.

The second issue concerns the fidelity of geometric representations. Most applications demand geometric fidelity and cannot tolerate artifacts such as spurious oscillations or artificial discontinuities that arise in most image processing and TIN software. It may be permissible to miss some low-priority geometry because of bit budget but introducing artifacts that are not present cannot be tolerated.

2.4 Representation systems

Images are typically transformed to multiscale representation systems such as wavelets, curvelets, or local time-frequency atoms. While multiscale representations are essential to efficiently capture both global and local structure in terrain, the use of the standard explicit representation systems fails to capture the essential geometry and topology because they view terrain as a functional surface. This is unsatisfacotry in many application areas. For example, autonomous navigation rests on faithful representation of navigable areas. This requires at a minimum the capturing of the dominant inherent topology in terrain.

2.5 Point cloud data

Most terrain encoders, such as Digital Elevation Maps (DEMs), take data on a structured grid as input. However, raw sensor data of terrains are often point clouds and not structured. Moreover, missions such as autonomous navigation, battle assessment, target acquisition and surveillance from sensor swarms must deal with streaming point cloud data subjected to noise. These cannot be handled with traditional tools for DEMs which entail structured grids. Scattered data methods such as radial basis functions are not able to provide the desired local multiscale decompositions. Moreover, in these applications, processing must be done real-time and often with limited computational resources.

2.6 Fast processing and rendering

Many defense missions require real-time processing of sensor data to 3D models within the limits of the available compute power. Other missions will require fast and cheap rendering of the encoded bitstreams, possibly on hand-held devices, subjected to possible bit loss in communication channels. Most terrain processing software is developed with no constraints on compute power and is therefore not implementable in real-time scenarios.

Keeping these deficiencies in mind, it is clear that to achieve the performance levels demanded in application will require a rethinking of the foundations of terrain modeling. We propose to develop a theory for terrain processing directed at correcting the deficiencies noted above with an eye towards the typical application domains. The details of our proposed research program are given in subsequent sections and will involve (i) developing a theory which will uncover new representation systems utilizing implicit representation of surfaces, (ii) creating new algorithms to extract geometry and topology from point cloud data, (iii) prioritizing the extracted geometry and topology with respect to application driven metrics,

(iv) generating terrain surfaces from point cloud data, (v) testing and developing software in real defense applications, (vi) collaborating with DoD users of terrain modeling.

3 Proposed Research

We propose to develop a new platform for terrain processing based on an integrated (hybrid) system consisting of both explicit and implicit representations. Our rationale for such a system was already given above when we discussed the deficiencies of present-day terrain processing platforms. This section will discuss several challenges to developing and numerically implementing such a system. Before describing these challenges, we give our vision of the general form such a new platform will take.

A surface (or portion of a surface) can be described either explicitly or implicitly. An explicit representation usually takes the form of a parametric representation of the surface. In terrain applications, however, we shall restrict such explicit representations to be locally the graph of a function in some coordinate system. The departure here from the usual terrain models is that we do not assume that this coordinate system is the standard x, y, z system and so it is not necessary that the surface be the graph of a function in the standard coordinate system. We have already mentioned some of the structures such as critical points, monotone regions, level curves, ridge curves, and drainage curves that serve as our building blocks when working with explicit representations. We want to retain these primitives in our new system, but we also want to add to them considerably by utilizing implicit representations.

In an implicit representation, the surface is described as the set of points which solve an equation $F(x, y, z) = 0$. Thus, the surface can be viewed as the boundary of the level set of a function F defined on a domain in $\mathbb{R}^3$. There are many functions F which yield the same surface. One particularly useful choice is the function F_d which gives the signed distance of the point (x, y, z) to the surface. The sign will be positive if the point is exterior to the surface and negative otherwise. This choice is particularly useful in line of sight calculations and autonomous navigation. A point (x, y, z) is in the line of sight from (x_0, y_0, z_0) if F_d does not change sign on the line segment connecting these two points. In autonomous navigation, a fly zone can correspond to the region $F_d \geq \delta > 0$ where $\delta > 0$ is some prescribed tolerance.

The most essential step in an implicit representation of a surface is a separation and classification of the whole space domain into two regions: interior and exterior. The boundary between these two regions is the surface. For representation, compression and reconstruction, one only needs to know and store information near the boundary. Of course the interior region can and will generally, be multiply connected, e.g. many buildings separate from each other, all defined simply through one scalar function.

Implicit models are a natural choice for the modeling of 3D urban terrain because of their flexibility and robustness in dealing with complicated topology. Every object can be regarded as solid or volumetric. Hence one can mark regions that are inside structures or underground as interior. The whole complementary region is marked as exterior. Line-of-sight information can be used to distinguish interior and exterior regions. Non-genus-0 topology poses no extra difficulty. Other information, such as connectedness, can also be incorporated to compute the correct topology [38, 36]. Usually the interior region is composed of multiple disconnected components which are associated with the interior of different objects. Many operations and manipulations become very simple using implicit methods, for example, Boolean operations, finding intersections, visibility and path planning [14],[34].

The advantages of implicit representation in image processing are now well demonstrated. They lead to state-of-the-art denoising and deblurring algorithms [25]. There are several compelling reasons to utilize implicit representations in terrain processing. The first is captured in the remarks above on line of sight and navigation. The second has to do with efficient encoding. Some surfaces or portions of surfaces are much easier to describe in implicit form. This is the case for most man-made structures. Consider for example the cylindrical surface $x^2+y^2=r^2$, $0 \le z \le L$, which could correspond to a portion of a telephone pole or light pole. In implicit form this surface can be described by very few bits. Its description by explicit methods (for example approximation of its level curves by piecewise linear functions) would be much more costly. Another point is that implicit representations more easily describe the topology of the surface and connectivity regions.

Which representation system is better - explicit or implicit? If there were a simple answer to this question, then the other system would soon disappear. In terrain modeling both have advantages. For example in encoding a surface into a bitstream there will be portions of the surface which will be cheaply encoded by implicit methods while for other portions going to an implicit method will unnecessarily eat up bits (because we have to describe F while we are only interested in the surface). Thus, we would like to have one integrated system which has the potential to utilize both explicit and implicit methods.

Our vision is that the integrated system will be built on an hierarchical tree decomposition carrying some similarities to hybrid wavelet-based methods (see [27]). We take a large cube Q_0 that captures the surface and the region in which our application domain will operate. We shall simultaneously build our surface and the distance function F_d in a multiscale fashion quite analogous to the wavelet multiscale decomposition. On Q_0 we extract coarse elements which will be either explicit (for example a network of curves) or implicit (a first approximation to F_d). These coarse elements are what we record. They can be used to give a coarse description of the surface and the function F_d . We then subdivide Q_0 into its children and consider the residual which is the true surface less the approximate surface that could be constructed from what we already extracted on each child. We then treat each of the children and the residual surface as we did Q_0 and the original surface. We extract explicit and implicit elements on each child. We continue in this way to fine scale.

This representation will have a tree structure which we shall exploit in analogous ways to image processing and numerical differential equations (see e.g. [35, 22, 17, 7, 3]). Namely, we create a sequence of nested trees. The initial tree contains the highest priority information that has been extracted. Each new tree adds additional information. The tree will go deeper in regions where we need fine resolution and stay shallow when the coarse resolution is already satisfactory. The fine resolution will typically take place on cubes which intersect the surface and where the surface is complicated. Coarse resolution will probably be sufficient on cubes which are away from the surface because a coarse resolution of F_d is usually sufficient.

Bringing such a terrain processing platform to fruition will involve several theoretical and computational challenges. We now describe the specifics of these challenges including some of our ideas for meeting them.

3.1 Theoretical Foundations (USC, TAMU)

We propose to develop a cohesive mathematical theory which will be the foundation for our development of terrain modelling. This theory will classify mathematical surfaces in terms of their simplicity or complexity vis-a-vis how well they can be approximated (or encoded) in the Hausdorff metric using a multiscale implicit/explicit decomposition. The classification will determine how well a surface can be compressed in these metrics. In other words, we shall provide a rate-distortion theory for the compression of surfaces.

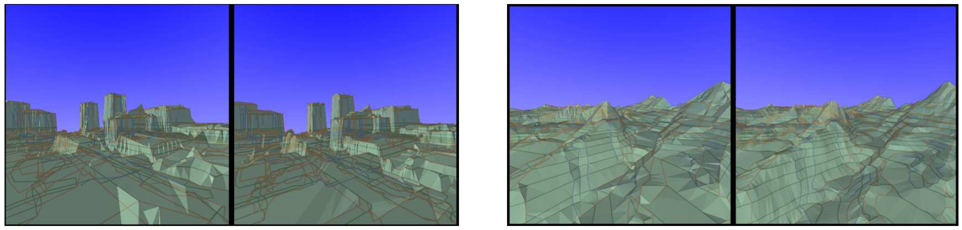
Such a theory for image encoding already exists [9, 8, 7, 10] and accurately describes the performance of classical wavelet-based encoders such as the zero-tree encoders [30, 29]. The theory measures image smoothness in terms of its regularity in a scale of Besov spaces.

The theory we shall develop for surfaces will be much more complex and will necessarily introduce a new class of anisotropic function spaces. The beginnings of such a theory already exist in [12]. This work introduces a way to measure the smoothness of a surface which is the graph of a function f defined on a domain in $\mathbb{R}^2$. The smoothness of the surface is determined by two ingredients: (i) the smoothness of the level sets $\Omega(z)$ of f at height z, and (ii) how smoothly these level sets evolve with changes in z. This leads to two smoothness parameters s_1, s_2. The first measures the smoothness of the level sets and relates to how well these level sets can be compressed using nonlinear methods. The second relates to how many level sets are needed to accurately describe the surface. Using these ideas, smoothness spaces $\mathcal{F}_p^{(s_1,s_2)}$ are defined and shown to accurately predict which surfaces will be compressible to accuracy Cn^{-s} using roughly n bits and with distortion measured in the L_p norm. Namely, it is proven in [12] that whenever $f \in \mathcal{F}_p^{(s_1,s_2)}$, then using $n \log n$ bits, the surface of f can be captured to accuracy n^{-s} with $s = (\frac{1}{s_1} + \frac{1}{s_2})^{-1}$ and distortion measured in L_p.

It is important to note that the spaces $\mathcal{F}_p^{(s_1,s_2)}$ are completely different from classical smoothness spaces such as the Sobolev and Besov spaces. For example, characteristic functions of smooth regions are not smooth in classical spaces since they have large jump discontinuities along curves. However, they are very smooth in these new spaces and their efficient encoding is correctly predicted. These new spaces are also completely anisotropic in the way they measure smoothness. They have no directional bias. The properties of these new function spaces are innovative and make them particularly attractive not only for classifying surfaces, but also for other areas of applied analysis such as evolution equations.

The spaces $\mathcal{F}_p^{(s_1,s_2)}$ lead us in the right direction as to how to decompose and encode surfaces. For example, these theoretical results are at the core of the terrain encoder developed at the University of South Carolina's Industrial Mathematics Institute (IMI) [4]. Figure 1 shows how a monotone section of terrain is encoded via level sets. A family of level curves is extracted from this section. Each curve is encoded using a multiscale decomposition developed in [2]. The family of curves is then blended into a surface using methods that flesh a surface from a network of curves. Our goal is to enlarge this theory to address the more extensive integrated representation scheme describe above. Here are some of the problems which must then be addressed.

New building blocks of implicit curves and surfaces. The spaces $\mathcal{F}_p^{(s_1,s_2)}$ measure smoothness through level sets. For general surfaces, the notion of level sets has to be replaced by other primitives. We intend to incorporate more general sets which are the intersection of the surface with a plane. To describe or encode such a region we need only give its



a) b)

Figure 1: Coarse and fine terrain approximations based on *level set derived* maximum monotone sections and ridge/ravine curves for a) urban, and b) rural terrains.

boundary which in general is a network of curves. Rather than restrict ourselves to explicit representations of these curves, we shall also admit implicit representations as we have emphasized at the beginning of this research section.

We shall also consider as primitives surface elements which have a simple explicit or implicit description. Thus, instead of just viewing the surface as built up from level curves we will view it as built up from a network of curves and surface patches which have a simple implicit or explicit description.

Non-functional metrics. Membership of a function f in the space $\mathcal{F}_p^{(s_1,s_2)}$ predicts how well it can be encoded if the distortion is measured in the L_p norm. However, as we have argued earlier, the L_p norms are not suitable for measuring terrain distortion. Therefore, in the development of our new theory we shall utilize the Hausdorff metric to measure distortion. We already have some results in this direction and a clear vision of what is to be done. For example, let us return to the setting of a monotone section of a surface. Two criteria will determine the classification of smoothness. The first is how well the level curves of the surface can be approximated in the Hausdorff metric. The second is how the level curves evolve (distortion measured in the Hausdorff metric) as the level z changes. Suppose for example that we wish to approximate a monotone section of a surface to accuracy ϵ. We choose levels $z_1 < z_2 < \cdots < z_n$ such that the level curves for any two consecutive levels z_j and z_{j+1} differ by at most $\epsilon/2$ in the Hausdorff metric. Then we approximate and encode each of the level curves to accuracy $\epsilon/2$ in this metric. This network of approximate curves can be fleshed into an approximate surface using a procedure given in [12]. In summary, our new smoothness spaces will be developed with respect to the Hausdorff metric rather than function metrics.

Rate distortion for the new classes of surfaces. After we have correctly introduced these new classes of surfaces we shall describe how well these surfaces can be encoded with distortion measured in the Hausdorff metric. The encoding of the primitives should be relatively straightforward. The main challenge will be to give a procedure for fleshing out the surface from these primitive elements and proving that this fleshing procedure yields the right order of approximation. We envision describing the surface off of the primitives by some sort of set interpolation method (see e.g. [13] or some subdivision method (see [41]).

3.2 Implicit Methods to extract Geometry/Topology (UCI,UCLA,UT)

Very effective methods exist for extracting the explicit elements of terrain surfaces. For example, the marching squares method is used to extract level curves and watershed algorithms are used to extract drainage curves. The extraction of implicit representations of surfaces has also been extensively studied at both the theoretical and algorithmic levels. We describe next the state of the art algorithms for extracting implicit representations from point cloud data and the remaining challenges that will be addressed in this proposed research.

Implicit methods begin by analyzing and preprocessing the raw point cloud data. This step is important to make the more complicated operations that follow efficient and robust especially in the presence of noise. Our earlier work has developed several high performance algorithms which can be utilized for preprocessing both the original point cloud data and later discrete resolutions of the surface. Feature extraction, filtering and hole filling can be accomplished through a tensor voting procedure [24]. This is a robust nonlinear filtering of point-cloud data that extracts coherent features. In particular it gives a good indication whether a data point lies on the surface and it also estimates the normal to the surface at that point. It easily finds outliers. The extracted features and information can be used for removing outliers and for surface reconstruction from a highly noisy point cloud data [23]. These techniques are illustrated in Figure 2.

Point cloud data may have very dense and very sparse regions. To fill in the sparse regions we use saliency and tensor fields. These methods are a bit slow in practice (although improvements in efficiency were made in [23]). One of the goals of the proposed research will be to improve the performance of these algorithms by making them more local.

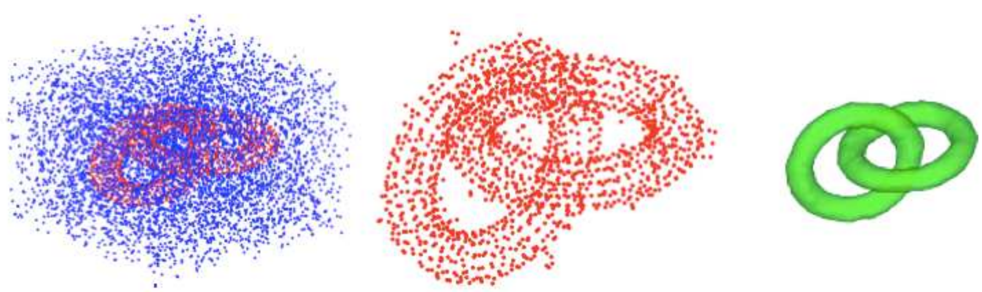


Figure 2: a) Data with 500% noise, b) Data filtering by tensor voting, and c) Reconstructed surface.

Another important processing algorithm is sweeping and tagging [38],[23]. The point cloud data is segmented into various simply connected components on different scales based on the distance contours of the data set and on a connectivity condition. Each component can be further characterized by its Hausdoff dimension and its enclosed volume. These characterizations are useful in identifying regions where there are thin objects and where grid refinement will be needed for accurate representation. Also distance contours can be regarded as an approximate offset of the true surface and can be used as a good initial reconstruction or visualization. For nonuniform data an adaptive distance contour has to be used according to a local sampling density. For instance, a distance contour with smaller value gives a better approximation of the real surface. On the other hand if the value for the distance contour is taken too small compared to the sampling density, the distance contour will not be connected. An efficient marking algorithm [36] is available to label and extract different connected components for visualization or other operations.

After preprocessing the data, an implicit representation can be found for the surface. We have mentioned earlier that there are many such representations. We wish to find one of these whose zero set is a very faithful representation of the surface. Three crucial issues arise:

(1) how to infer interior and exterior from the point clouds so that the sign of the scalar field and the topology of the implicit model are consistently defined, (2) how to compromise between interpolation error and noise level, and (3) how to detect smoothness from the data and enforce adaptive regularity for the scalar field.

In [39],[40] a minimal surface model was proposed as a method to find an implicit representation of the data. Roughly speaking this method looks for an implicit function with good smoothness whose zero set is an accurate fit of the discrete data. Once this implicit representation is found, we have a good representation of our surface and we can go further and find the distance function for the surface. These algorithms perform well for smooth surfaces but will need improvements to handle more complicated terrain, especially urban terrain. For example, edges and corners of buildings in urban terrain are penalized in the minimization and hence are lost in the smoothing. One of our goals in this project will be to enlarge the scope of our algorithms to retain these features.

Once we have obtained the minimal energy representation of the surface, we can construct the distance function representation of the surface which we have argued is invaluable for certain application domains. A distance function representation is easily derived from the minimal energy representation. The information needed for storage and reconstruction is contained on its values at grid points near the zero level set, since away from this set the function is defined uniquely by a partial differential equation, $|\nabla u(x)| = 1$. An extremely efficient algorithm, the fast sweeping method [37], is available to construct the whole distance function. A simplex free adaptive tree fast sweeping method [5] can be used on adaptive or octree data structure. An adaptively sampled distance fields strategy [14], which is a bottom up approach, can be applied for optimal sampling with desired accuracy. The procedure is as follows: when the distance field on the coarser level approximates the distance field on the finer level well by interpolation, the finer level can be removed. Of course this procedure is carried out locally and adaptively. Efficient compression techniques can be applied to the distance field near the zero level set. Also ENO (essentially nonoscillatory) types of interpolation techniques will be useful for representing nonsmooth surfaces, as described in later sections of this proposal.

One of the main challenges is the representation of thin objects. In particular 3D urban terrain data is intrinsically multi-scale and has large variance in feature size. An efficient and robust hybrid and/or adaptive model will be developed for practical applications.

To obtain high performance of implicit representations for compression, we advocate building a library of simple implicit functions which can be represented by a few parameters. We would then seek to find local representations of the surface by elements from this library. This will require changing the minimizing energy approach described above and will be one of our main goals in this research project.

3.3 Tree approximation and encoding (RU, USC)

Once we have extracted the explicit and implicit primitive elements of the given surface relative to our hybrid representation system, we will have to prioritize them and organize them into our tree. The prioritization of the primitive elements will be based on distortion in the Hausdorff metric. For example, to assess the importance of a given node of the tree, we will evaluate the distortion that would occur in the Hausdorff metric if this node and all its descendants were removed from the tree.

The information at each node of the tree will be encoded into a bitstream using traditional ideas from progressive encoding. The bitstream will contain information necessary to recover both the surface and the distance function F_d. Our challenge will be to organize the bitstream in such a way that when only one of these entities is requested (for example only the surface) then it can be extracted from the entire bitstream with little overhead. An additional property we seek for the encoding is the capacity to "burn-in" to a chosen region of the surface without additional overhead. Namely, if a client asks for higher resolution in a certain local region of the surface, then we want to extract from the bitstream only the bits that correspond to updating the resolution of that region. Such burn-in capacity in image encoding was introduced in [9], and we shall follow the ideas there for surface encoding.

One of the main challenges to the hybrid system will be to seamlessly decode the explicit and implicit components. We plan to follow the ideas of the wedgeprint image encoder [35] that successfully combines two diverse representations: the linear wavelet transform and partition-based wedgelets. The unifying construct in both this image coding case and our surface encoding case is a multiscale tree structure. Since both components (wavelets/wedgelets or explicit/implicit) can be interpreted as existing on the same tree, we can use dynamic programming to make the best choice of representation at each resolution.

3.4 Point Cloud Data (UCI, USC, UT, VT)

A demanding task for terrain processing is to find a good surface approximation to raw point cloud data, generated from one or several sensors. Here one has to deal with potential noise in the point cloud due to inaccuracy in measurements, sensor noise, and ambient noise. Since these noise characteristics are not known, we have advocated in our previous work the application of learning theory since it does not require knowledge of the noise distributions. Our past work has built data-fitting algorithms for point cloud data which use adaptive refinement and piecewise polynomials as the representation system [1].

The major difficulty encountered in processing point cloud data is to capture the topology and geometry only to the extent that the data allows. Although the surface is two dimensional in certain regions it will appear as one dimensional (wires for example), while in others it will appear as if coming from a three dimensional solid. For example, LIDAR responses from trees or other types of vegetation will appear almost as if it were data from a 3D solid. In this case, our goal will be to extract the envelope of this solid and not the fine nuances of the surface since the latter will not be justified by the accuracy of the data.

We propose to develop new algorithms for learning which will address these finer problems of capturing the geometry and topology to the extent supported by the data. Specifically, we shall incorporate the following new ingredients into our algorithms and analysis.

Explicit/implicit approximation. The first improvement is to utilize our explicit/implicit primitive elements and the multiscale tree structure in place of piecewise polynomials on adaptive grids. This will require several new ideas. First, we shall need to understand how to extract these elements from noisy data. Here we shall seek to prove a theorem which will describe the optimal complexity of the tree given the size of the data set. Too large of a tree will overfit the data (fit the noise) and too small of a tree will not extract the full available information in the data. We would like this theorem to establish optimal performance for our generalization of the $\mathcal{F}_p^{(s_1,s_2)}$ spaces discussed earlier. Another major issue will be to guarantee accuracy of fit in the Hausdorff metric and not in a least squares metric.

Our intention in this setting is to first establish lower bounds on the optimal performance of such learning algorithms. This will generalize the lower bounds given in [11] by allowing this new form of nonlinear approximation and by allowing error to be measured in the Hausdorff metric. Then, we shall construct numerical algorithms which match this performance on our new function classes. The challenge in constructing these algorithms will be the fact that we measure the distortion in the Hausdorff metric. Almost all bounds for performance in learning theory are based on measuring the distortion in the $L_2(\rho_X)$ metric where ρ is the underlying probability distribution which generates the data.

Classifying the dimension of the data. Our vision for seamlessly treating the different local dimension of the data is to incorporate learning theory with sparse occupancy trees and multiscale analysis. We shall view 3D space as partitioned into a multiscale family of cubes. Each cube which contains sufficiently many data points will be classified by a dimensionality dictated by the data. This dimension can be determined by using local principal component analysis on the cube and near neighbors. The complexity of the three dimensional tree will be simplified by the fact that we consider only cubes which are occupied by data (sparse occupancy trees).

3.5 Multi-Sensor Data (VT, PU, RU)

3.5.1 Sensor Network Data

A particularly challenging aspect of the proposed research will include the synthesis, processing and approximation of urban and battlefield environments from *multiple mobile sensor sources.* Figure 3 illustrates one scenario - important to net-centric warfare - which integrates multiple unmanned ground vehicles, and unmanned air vehicles to form a heterogeneous ad hoc network of diverse sensors.

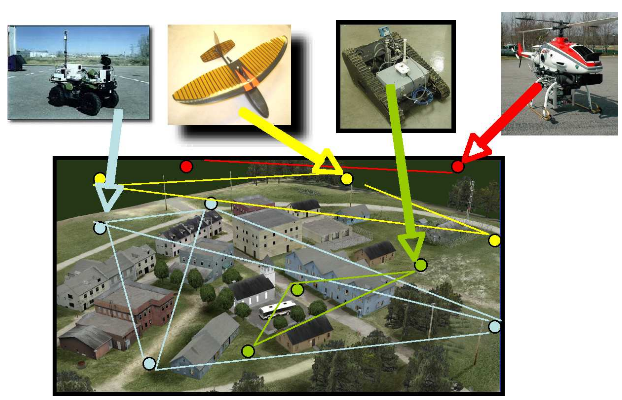


Figure 3: **Mobile ad hoc sensor net of Ft. Benning MOUT Site Geometric Database.** Heterogeneous team asynchronously collects vision, LIDAR, acoustic fields; generates multifield point cloud databases.

The sensors can vary in nature: they may collect optical images in the visual spectrum, hyperspectral imagery, LIDAR data, acoustic fields, etc. All of these vehicles and the associated sensors are available to the research team through the Joint Unmanned Systems, Training and Research Laboratory associated with Virginia Tech and described in more detail in Section 3.6.2 . The challenge, mathematically speaking, is to obtain *distributed, real-time* algorithms for multi-field data. Again, point cloud data from multiple sensor sources is a particularly relevant data stream. It should be emphasized that the net-centric warfare challenge embraces the difficulty of adjusting the computational budget and throughput bandwidth to the mission at hand. The derived algorithms must be scalable. Figure 3 emphasizes the need for real-time, bandwidth scalable geometry approximation algorithms. In some cases, when computational budgets are not limited, a mission may require *approximation fidelity* commensurate with photorealistic rendering. However, in many applications, the throughput is severely limited by the real-time (30-60 hz) vision processing requirements. Figure 4 illustrates our AVCAAF work in autonomous flight and a dynamically computed path of a micro-air-vehicle that employs vision-generated sparse point clouds to reconstruct, and thereby avoid, obstacles that arise in guidance, navigation and control in urban environments. The point cloud is derived from Structure From Motion estimates and this work emphasizes that learning theoretic methodologies in [1] are well-suited to real-time applications [18, 26] with extremely limited computational budgets.

Figure 4: a) High resolution virtual Ft.Ḃenning simulator, b) Vision-based 2D feature points, c) Real-time progessive mathematical learning of resulting point cloud, coupled to a receding horizon, adaptive controller in a simulation of an autonomous MAV navigating through a corridor at Ft. Benning.

3.5.2 Distributed Learning and Pattern Recognition

Our approach to integrating multi-sensor information is through learning theory. Reproducing kernel methods are a popular and highly successful approach to nonparametric learning and pattern recognition. These methods take as input a training set $\cup_{j=1}^{m} S_i = S = \{(X_i, Y_i)\}_{i=1}^{m}$ and, in the least-squares regression setting, output a function $f_\lambda : \mathcal{X} \to \mathcal{Y}$ which solves the global optimization problem formulated as

$$f_\lambda := \operatorname*{argmin}_{f \in \mathcal{H}_K} \Big[\sum_{i=1}^{m} (f(X_i) - Y_i)^2 + \lambda \|f\|^2_{\mathcal{H}_K} \Big] \tag{1}$$

where $\mathcal{H}_K$ is a reproducing kernel Hilbert space. Solving this global problem (1) is difficult in distributed settings with resource constraints, when there are a collection of sensors, each observing an example (X_i, Y_i). One approach we have recently begun to explore for solving this problem relies on local (and iterative) sharing of data, not entire functions, and thereby addresses the practical weakness that limits the effective applicability of many other methods (e.g., the incremental subgradient approach) for large scale problems.

In this approach, sensor i queries its neighbors' data (X_j, Y_j) for all $j \in N_i$ where N_i denotes the network neighbors of sensor i. This local data is used to compute a global estimate for the field by solving the variational problem (1) just sum of neighbors N_i.

Each node computes such an estimate. Thus, we can iterate through the network allowing each sensor to compute a global estimate using only local data. The key idea for propagating information is to couple this iterative process using a set of message variables. Specifically, sensor i maintains an auxiliary message variable $z_i \in \mathbb{R}$, which is interpreted as an estimate of the field at X_i. Each sensor initializes its message variable according to its initial field measurement, i.e., $z_i = Y_i$ to start. Subsequently, the sensors perform a local computation in sequential order. In turn, sensor i *queries* its neighbors' message variables and computes $f_i \in \mathcal{H}_K$ as the solution to local problem using $\{(X_j, z_j)\}_{j \in N_i}$ as training data and then *updates* its neighbors' message variables, setting $z_j = f_i(X_j)$ for all $j \in N_i$, which successively propagates the newly updated message variables out globally through rings of neighbors.

Two additional modifications are needed to fully specify the algorithm (see Figure 5). First, multiple passes (in fact, T iterations) through the network are made; for convenience, denote sensor i's global estimate at iteration t by $f_{i,t} \in \mathcal{H}_K$. Second, each sensor controls the "inertia" of the algorithm, by modifying its local variational problem via the parameter $\lambda = \lambda_i$. Specifically, at iteration t, $f_{i,t} \in \mathcal{H}_K$ is found successively to minimize the local problem using its neighbors' message variables from iteration $t - 1$.

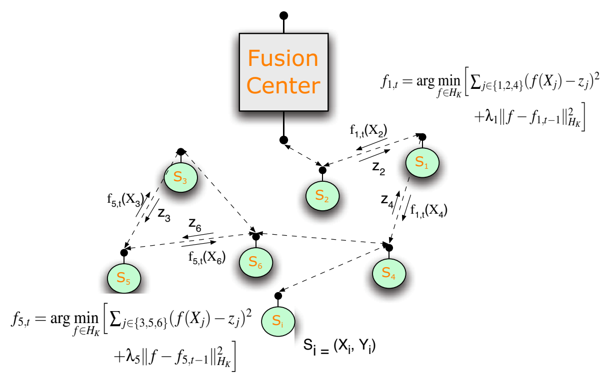


Figure 5: Training Distributively with Alternating Projections

This approach is inspired by methods from graphical models, belief propagation, message-passing, etc. The approach is independent of assumptions that couple the kernel $K(\cdot, \cdot)$ with the network topology. Thus, prior domain knowledge about $\mathbf{P}_{XY}$ (the joint distribution of (X, Y)) can be encoded in the kernel; the training algorithm approximates the centralized estimator as closely as the communication constraints allow. Secondly, sensors only share estimates of functions at a small number of points, and not the full functions themselves, thereby significantly broadening the scope of applicablility. We propose to refine and enhance this basic approach to distributed learning and pattern recognition, apply the method to learning and classification for urban terrain data, and analyze the performance of these methods for the urban terrain applications of interest.

3.6 Application Domains (UCI, UCLA, USC, UT, VT)

3.6.1 Methodologies

Among the numerous application domains discussed thus far in this proposal, one important goal is to develop sparse representations that facilitate efficient solutions to problems arising in computational geometry and navigation [15] in general environments. Both the adaptive learning theory methodologies and the proposed implicit surface models hold great potential in mission planning in an urban environment.

We propose two approaches to computing visibility (line-of-sight) that can be seamlessly integrated into the overall program. The first is an implicit ray casting algorithm that assumes a level set representation of the occluding objects and creates a visibility level set function [34]. The visibility function is continuous and can be extremely useful in applications of pursuit-evasion in urban environments [6].

The second approach is developed specifically for point cloud data [20]. This algorithm projects point clouds onto a sphere centered at an observing location and performs essentially nonoscillatory (ENO) interpolation [16] on the projected data. Consequently, open surfaces can be handled and curvatures of the occluding objects can be easily approximated and used in many ways. Similar to the level set representation, this approach can handle complicated geometries and even curved lines of sight. The computed data can easily be converted to the level set formulation for seamless integration with the proposed level set model for point clouds. Furthermore, this algorithm applies directly in the situation where rays curve due to inhomogeneity in the media.

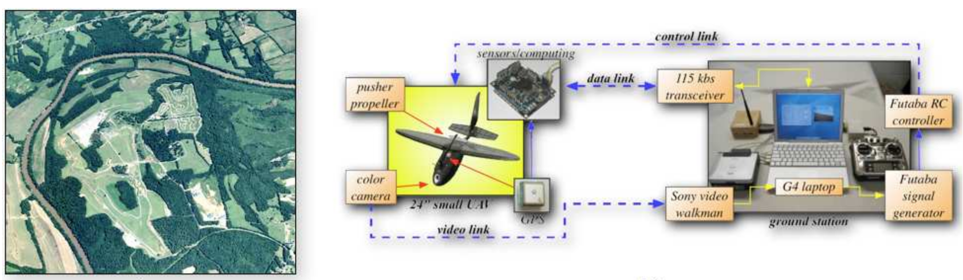
We extended this point cloud visibility algorithm into a novel approach for mapping and adaptively learning a partially unknown environment. See [20] and related work of La Valle et al [33],[28],[21]. The algorithm assumes that either a point cloud sampling of the entire environment is given or a point cloud of the visible surface is sampled on-the-fly. The idea is to use the visibility information at the present vantage position to determine the next vantage position in order to maximize the gain in visibility information. In particular the distance to the visible portion of the surface and its curvature (computed directly from the given point cloud) are indispensable pieces of information for our algorithm and for many further applications [6]. They are inherently easy to obtain from our formulation but pose a major computational bottleneck for other approaches. A variant of this algorithm has been successfullly implemented in the robotics lab at UCLA [19]. We will develop a robust 3D generalization of this algorithm and incorporate it into the proposed project.

Adaptivity can be achieved using a hierarchical decomposition of the domain. In many applications requiring visibility, a natural refinement criterion involves the distance to the visible parts of the surface. The geometry (curvature) near the physical boundary of visibility and occlusion also greatly influence the resulting computation. Hence, we shall combine the distance and curvature information to formulate the refinement criteria. A library of primitive shapes can be used for adaptive modification of an implicit surface.

3.6.2 Validation and Experimentation

Members of our research team have participated in several projects supported under the DoD Multidisciplinary University Research Initiative (MURI) programs. Our experience indicates that the most successful MURI programs have very strong proof-of-concept experimentation, military laboratory collaboration and direct paths for transition to the warfighter.

This research team proposes an extensive in-field validation of its software and algorithm development. One significant difficulty is that bona-fide DoD laboratory testing at military sites can be prohibitively expensive and time-consuming. Military test sites are typically equipped to support *procurement and certification* tasks for products. The verification and validation planned by this proposal, in contrast, will require trial-and-error experimentation needed for *research and development*. Tasks include analytical development, software programming, hardware integration and validation. Verification and validation of the research will be tested in real-time in a variety of test scenarios: software/hardware-in-the-loop simulation, immersive/virtual environment simulations and field tests. The field tests will include a number of ground and air vehicles running the developed algorithms in real-time implementations. These tests will be carried out in collaboration with the JOint Unmanned Systems Test, Experimentation, and Research (JOUSTER) Facilities. JOUSTER is a partnership between Virginia Tech and the Institute for Advanced Learning and Research (IALR). JOUSTER is affiliated with the Army Research, Development, and Engineering Command's (RDECOM) Simulation and Training Technology Center (STTC), and the Department of Defense (DoD) Joint Ground Robotics Enterprise (JGRE). Together, these groups are establishing facilities to support unmanned aerial, ground, surface, and underwater vehicle experimentation over a wide variety of terrain and weather conditions. The JOUSTER site is located with IALR in Danville, Virginia - a two hour drive from Virginia Tech. In effect, this MURI team will have access to a DoD created and supported experimentation, verification and validation site.



a) b)

Figure 6: Application Domains and Tech Transfer. a) JOUSTER site, b) AVCAAF MAV project.

The unmanned vehicle platforms available for verification and validation include a fleet of 5 autonomous two-seat electric vehicles and 2 all-terrain vehicles for networked, simultaneous source collection from multiple cameras and laser scanners (LIDAR). Autonomous rotorcraft include one Yamaha RMAX and two Bergen helicopters that can be configured to carry a variety of sensing payloads including vision, acoustic and LIDAR instruments. Fixed wing autonomous vehicles include several RASCAL aircraft with various camera payloads. JOUSTER operation areas include a dedicated 30-acre test field, a 3.27 mile paved racetrack, a 320-acre reconfigurable off-road track, a motorcross track, and other off-road trails. By utilizing JOUSTER MIP (Mobile Instrumentation Platform) stations and wireless instrumented payloads, these sites can be converted into an instrumented site to support unmanned vehicle experimentation. A 12,000 sq-ft building devoted to JOUSTER operations has recently been constructed. The facility has a command and control station that controls, monitors, and records data from JOUSTER instrumented sites. The command and control station also allows DoD customers to tie into the instrumented sites via the Internet.

3.7 Technology Transfer

Our group already exploits the use of terrain maps in battlefield scenarios. USC has an intense collaboration with Radiance Technologies (POC: Dr. A. Thies, Director of Advanced Technologies) to transition IMI Surface Processing Software to DoD applications. This includes an operating STTR Phase I to port the IMI surface compression engine and its learning algorithms to real time targeting through the surface assimilation of LIDAR point cloud data, geometric feature extraction, compression, and tracking. DoD customers include Joint Warfare Analysis Center (JWAC) (POC: D. Castleberry, Dalhgren), and Night Vision Systems (POC: Mike Barwick). The research project proposed here will provide theoretical foundation for the technology to be migrated, will enhance these efforts and provide increased military capabilities in these important application areas. USC and VT participate in a MURI program supported by AFOSR and Eglin AFRL-MN to enable autonomous flight of micro aerial vehicles in urban terrain. USC also has a long standing collaboration with Naval Air Warfare Center (NAWC) China Lake (POC: Gary Hewer).

UCLA, UCI, and UT personnel have a long standing collaboration with Level Set Systems including a current STTR and a DARPA GEO* contract (through NGIA) for geospatial representation, compression and analysis. Several techniques (the level set method, ENO, and total variation based image restoration) have found many DoD uses. For example, NAWC China Lake uses BV/L_1 decomposition for GEO* applications. This group is also closely attached to UCLA's NSF-funded Institute for Pure and Applied Mathematics (IPAM) which helps diffuse their our results and stay abreast of new developments.

4 Management Plan, Milestones, and Data Rights

This effort involves eight universities. Fortunately, several of our groups already have had long standing collaborations that have been only partially described in this proposal. This research project will establish six additional collaboration cells to address Tasks detailed in Sections 3.1 through 3.6, respectively (see Figure 7 a). The nodes correspond to participant universities and each connected colored subgraph corresponds to one collaboration cell. As the research progresses, the graph will be modified accordingly.

Collaboration Cells

Cell 1	USC*, TAMU	
Cell 2	UCLA*,UC-I, UT	
Cell 3	USC*, RU	
Cell 4	USC*, UC-I, VT,UT	
Cell 5	VT*, RU, PU	
Cell 6	USC*, UCLA, VT, UC-I, UT	

* denotes Team Leader

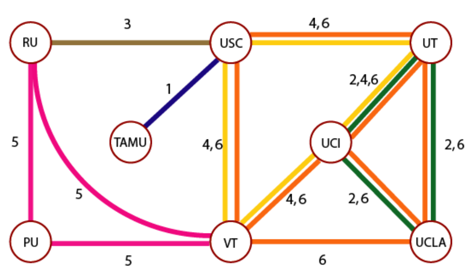


Figure 7: Collaboration according to Tasks in the Project Narrative

The lead PI, Ronald DeVore will be assisted by Stan Osher (UCLA), Robert Sharpley (USC) and Mark Pierson (VT) in the overall coordination of the group's efforts. Each collaboration cell has a team leader who will coordinate efforts under that research area. The lead university for each cell is indicated by an asterisk in the Table.

To ensure maximum collaboration and coordination of efforts we establish several modes of interaction. The kick-off meeting will orient researchers to their individual Tasks and insure an understanding of their contribution to the statement of work in relation to the overall goals of the project. These goals are formulated in terms of addressing the Research Concentration Areas (RCA's) outlined in the BAA, in response to which this proposal is offered. In Figure 8, we provide a chart of each Collaboration Cell's efforts toward each RCA by quarters during the initial 3 year Basic Funding period. This chart will be updated on an annual basis, and a corresponding chart constructed for the optional funding period.

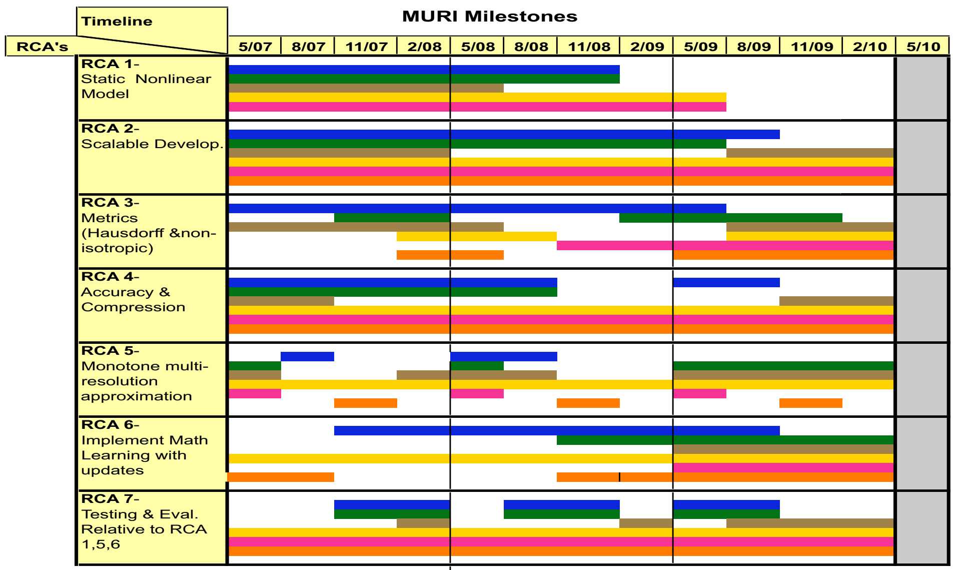


Figure 8: Timeline of Research Concentration Areas of Topic #28 of BAA06-28 addressed by Collaboration Cells from Figure 7 during the Basic Funding Period May 1, 2007 to April 30, 2010.

Semi-annual meetings of all participants will used to further coordinate our efforts. At the first semi-annual meeting of each year, progress to date will be evaluated and milestones will be refined for the current funding year. The second semi-annual meeting each year is intended to provide the opportunity to the Army program manager to use as a formal program review. Between the semi-annual reviews, each collaboration cell members will meet on a regular periodic basis through teleconference, videoconference, or in person. At an organizational level, the USC group will meet with each cell's leadership on at least a quarterly basis. Travel funding has been included in the budget for these collaboration meetings and technical assistance will be provided for freeware ACCESS GRID venues to support lost cost video conferencing and point-to-point communication for those on travel. Further collaboration involves the sharing of postdoctoral scholars among the research cells. This will facilitate joint efforts and provide thorough understanding of the developments of each component cell. We envision that postdoctoral personnel will work for extended periods at component institutions. We will promote shorter visits of PIs to collaborating institutions to provide the leadership to integrate the various technologies into a cohesive program. A collaborative web site will be maintained as a central depository for papers, meeting minutes, project descriptions, past presentations, schedules/milestone, URL member links and other team contact information.

Assertion of Data Rights

There are no claims of proprietary rights in pre-existing data.

RICHARD G. BARANIUK (Rice University)					
$390,001	03/02-05/08	Current	PI	.25 Acad	ONR: Higher-Dimensional Signal Processing via Multiscale Geometric Analysis
$237,197	03/04-02/07	Current	PI	.25 Acad	AFOSR: Multiscale Analysis, Modeling, & Processing of High-Dimensional Geometric Data
$750,000	09/04-08/07	Current	PI	.25 Acad/.75 Sumr	NSF: NeTS NOSS: AssimNet
$412,000	10/04-09/07	Current	PI	.5 Sumr	NSF: Multiscale Geometric Analysis for Higher-Dimensional Signal Processing
$400,000	08/05-07/07	Current	PI	.5 Sumr	NSF: NeTS NOSS: Adaptivity in Sensor Networks for Optimized Distributed Sensing & Signal Processing
$594,483	02/06-01/07	Current	PI	.4 Acad/.6 Sumr	DARPA/SPAWAR/ONR: Theory and Practice of Analog-to-Information Conversion
$399,999	04/06-03/07	Current	PI	.1 Acad/.4 Sumr	DARPA/ONR: Compressive Optical Imaging Systems-Theory Devices and Implementation
$90,000	05/06-09/06	Current	PI	.5 Sumr	ONR: New Theory and Algorithms for Compressive Sensing
$95,000	05/06-09/09	Current	PI	.5 Sumr	ONR: Manifold-Based Image Understanding
$1,450,781	10/03-12/06	Current	CoPI	.25 Sumr	NSF: Collaborative Research: SAFARI: A Scalable Architecture for Ad Hoc Networking and Services
PETER G. BINEV (University of South Carolina)					
$159,982	06/05-10/06	Current	CoPI	1 Sumr	ARO: Advanced Mathematical Methods for Processing Large Data Sets
$46,999	09/06-12/06	Current	CoPI		Radiance Technologies, Inc.: Software for Generating Geometrically and Topologically
RONALD A. DEVORE (University of South Carolina)					
$500,000	06/03-05/07	Current	PI	1 Sumr	ONR/DEPSCoR: Compression of Large Data Sets with Geometry
$700,000	06/05-05/08	Current	PI	1 Sumr	DoD/DEPSCoR: Nonlinear Methods for Supervised Learning: Defense Applications
$461,374	10/04-02/07	Current	PI	1 Sumr	DARPA: Highly Effective Geospatial Representation and Analysis
$479,999	10/05-09/08	Current	PI		ONR: Nonlinear Methods for Advanced Data Processing
$189,000	09/04-08/07	Current	PI		NSF: FRG: Collaborative Research in Algorithms for Sparse Data Representation
$159,982	06/05-10/06	Current	PI		ARO: Advanced Mathematical Methods for Processing Large Data Sets
$46,999	09/06-12/06	Current	CoPI		Radiance Technologies Inc.: Software for Generating Geometrically and Topologically
$500,000	06/07-05/10	Pending	PI	1 Sumr	DoD/DEPSCoR: Capturing Sparsity in High Dimensional Data
SANJEEV KULKARNI (Princeton University)					
$84,204	07/06-06/08	Pending	PI		Princeton Power Systems: Algorithm Research & Testing for a High Efficiency Solar Power Conversion Technology
$300,000	07/06-06/09	Pending	PI		ARO: Aggregating Probability Forecasts: An Approach to Hard/Soft Fusion - ARO
ANDREW KURDILA (Virginia Tech)					
$5,000,000	06/03-01/08	Current	CoPI	.2 Cal	AFOSR/Univ. of FL: Vision-Based Control of Agile, Autonomous Micro Air Vehicles And Small UAVs In Urban Environments
$6,623,756	05/04-03/07	Current	PI	.66 Cal	STTC RDECOM/NAVAIR, Develop the Joint Unmanned Systems Test, Experimentation, and Research (JOUSTER) site
$1,400,000	01/05-01/07	Current	CoPI		AFOSR/AFRL: A Research Institute for Precision Guided Munitions
$1,400,000	10/06-10/08	Current	CoPI	.1 Cal	ONR: Coordinated Sensing and Control for Surveillance and Tracking by Heterogeneous Autonomous Vehicle Teams
STAN OSHER (University of California, Los Angeles)					
$979, 694	09/03-02/07	Current	CoPI		NSF: New PDE Based Models and Numerical Techniques in Level Set Surface
$430,000	05/02-04/07	Current	PI	1 Sumr	Stanford Univ. subcontract to UCLA: An Integrated Approach to Multiple-Vehicle Sensing, Coordination and Control
$700,000	09/03-08/08	Current	CoPI		NSF: Collaborative Research-ITR-High Order Partial Differential Equations: Theory, Computational Tools, and Applications in Image Processing, Computer Graphics, Biology, and Fluids
$22,617,349		Current	CoPI	1 Acad	NIH, NCRR, NCBC, & NIGMS: NIH Roadmap Initiative for Bioinformatics and Computational Biology
$828,000	10/05-09/08	Current	PI	1 Sumr	ONR: Computational Crack Prediction Using Level Set Methods
GUERGANA PETROVA (Texas A&M University)					
$74,288	07/05-06/08	Current	PI		NSF: Analysis and Numerical Algorithms for Transport Equations and Related Problems
MARK PIERSON (Virginia Tech)					
$5,000,000	06/03-01/08	Current	CoPI	2.5 Cal	AFOSR/Univ. of FL: Vision-Based Control Of Agile, Autonomous Micro Air Vehicles And Small UAVs In Urban Environments
MICHAEL ROAN (Virginia Tech)					
$75,000	04/06-06/07	Current	CoPI	.25 Acad	ONR: Cooperative Processing Based on Pearl's Belief Propagation Algorithm: Torpedo Defense C&C
$75,000	10/06-09/07	Current	PI		ONR, Subaward: IED Interdiction Technologies
$100,000	02/06-01/08	Current	PI		ONR 2004 Young Investigator Award: Collaborative Information Processing for Undersea Systems
$149,692	12/05-04/09	Current	PI	.5 Acad/.9 Sumr	ONR: A Blind Source Separation Approach to High Resolution Acoustical Imaging
$75,000	12/05-09/08	Current	PI		ONR: University Laboratory Initiative,: An Image Compression Approach to Signal Processing For Cooperating UUVs
$630,000	01/07-12/08	Pending	PI	.05 Acad/.33 Sumr	ONR: Fast Coordination for Adaptive Group Behaviours and Distributed Signal Processing
$232,000	10/06-09/09	Pending	PI		ONR: A Turbo Approach to Distributed Detection and Estimation for Active and Passive Sonar
ROBERT C. SHARPLEY (University of South Carolina)					
$500,000	06/03-05/07	Current	CoPI	1 Sumr	ONR/DEPSCoR: Compression of Large Data Sets with Geometry
$461,374	10/04-02/07	Current	CoPI	1 Sumr	DARPA/DSA: Highly Effective Geospatial Representation and Analysis
$474,999	06/03-01/07	Current	PI	1 Sumr	UnivFL/USAF: Multiresolution Methods for Vision-Based Guidance, Navigation, and Control
$159,982	06/05-10/06	Current	CoPI	1 Sumr	ARO: Advanced Mathematical Methods for Processing Large Data Sets
$46,999	09/06-12/06	Current	PI		Radiance Technologies, Inc.: Software for Generating Geometrically and Topologically
RICHARD TSAI (University of Texas, Austin)					
$102,580	07/05-06/08	Current	PI	2 Sumr	NSF: Variational Approach to Optimization and Adaptivity in Problems Involving Visibility
$40,000	08/06-08/07	Current	PI		STTR: Implicit Level Set Based Software for Generating Geometrically and Topologically Accurate Urban Terrain
HONGKAI ZHAO (University of California, Irvine)					
$179,999	09/05-08/08	Current	PI		NSF: Efficient Numerical Methods for Material Transport on Moving Interfaces and Hamilton Jacobi Equations
$577,217	03/06-03/09	Current	PI		ONR: Model Based Image Analysis
$783,899	01/04-02/07	Current	PI		DARPA: Time-Reversal Imaging in Complicated Environment

Figure 9: Current and Pending Support for Principals

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[3] P. Binev and R. DeVore *Fast Computation in Adaptive Tree Approximation*, Numer. Math. **97** (2004), 193–217.

[4] P. Binev, R. DeVore, M. Heisberg, S. Johnson, B. Karaivanov, B. Lane, and R. Sharpley, *Geometric modeling and encoding of terrains*, preprint.

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on Intelligent Robots and Systems, (2003).

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Department of Electrical and Computer Engineering,
Rice University, Houston, TX 77005
Email: rich@rice.edu

Research Interests

Multiscale signal and image processing; 3-D geometry processing; Pattern recognition; Sensor networks

Education

Ecole Normale Superieure de Lyon (France)	Postdoc, 1992-1993
University of Illinois-Urbana	PhD in Electrical and Computer Engineering, 1992
University of Wisconsin-Madison	MSc in Electrical and Computer Engineering, 1988
University of Manitoba (Canada)	BSc in Electrical Engineering (with distinction), 1987

Appointments

2004-present	Victor E. Cameron Professor, Rice University, Houston, TX
2000-2004	Professor, Rice University, Houston, TX
1998	Rosenbaum Fellow, Isaac Newton Institute, Cambridge University
1996-2000	Associate Professor, Rice University, Houston, TX
1993-1996	Assistant Professor, Rice University, Houston, TX
1987	Research Assistant, National Research Council of Canada
1986	R&D Engineer, Omron Tateishi Electronics (Kyoto, Japan)
2001-2002	Sabbatical: ST (Paris), EPFL (Switzerland)

Honors

Co-Author on Passive and Active Measurement Workshop Best Student Paper Award, 2003; Fellow of the IEEE, 2001; Co-Author on IEEE Signal Processing Society Junior Paper Award (with M. Crouse, R. Nowak), 2001; IEEE NORSIG Best Paper Award (with E. Monsen, J. Odegard, H. Choi, J. Romberg), 2001; George R. Brown Award for Superior Teaching (Rice), 2001, 2003, 2006; University of Illinois ECE Young Alumni Achievement Award, 2000; Charles Duncan Junior Faculty Achievement Award (Rice), 2000; C. Holmes MacDonald National Outstanding Teaching Award (Eta Kappa Nu), 1999; Rosenbaum Fellowship, Isaac Newton Institute (Cambridge University), 1998; Office of Naval Research Young Investigator Award, 1995; National Science Foundation National Young Investigator Award, 1994; National Sciences and Engineering Research Council of Canada NATO Postdoctoral Fellowship, 1992

Professional Activities

Project Director: *COMPASS Project* – Multiscale network architecture and protocols for sensor networks
Founder: *Connexions* – open-access, community-based education (cnx.org)
Editorial Board: *Applied and Computational Harmonic Analysis, Transactions on Sensor Networks*
Chair: *IEEE Signal Processing Society*, Houston Chapter
IEEE Signal Processing Society, Technical Committee on Theory and Methods
Current Funding: NSF, DARPA, ONR, AFOSR, AFRL, Texas Instruments

Selected Publications

R. G. Baraniuk, M. Davenport, R. DeVore, M. Wakin, "The Johnson-Lindenstrauss Lemma Meets Compressed Sensing," submitted to *Constructive Approximation*, 2006.

D. Baron, M. Wakin, S. Sarvotham, M. Duarte, R. G. Baraniuk, "Distributed Compressed Sensing," submitted to *IEEE Transactions on Information Theory*, 2005.

M. Wakin, D. Donoho, H. Choi, R. G. Baraniuk, "The Multiscale Structure of Non-Differentiable Image Manifolds," *SPIE Wavelets XI*, July 2005.

S. Palchaudhuri, R. Kumar, R. G. Baraniuk, D. B. Johnson, "Design of Adaptive Overlays for Multiscale Communication in Sensor Networks," *IEEE Int. Conf. Distributed Computing in Sensor Systems (DCOSS)*, June 2005.

S. Lavu, H. Choi, R. G. Baraniuk, "Estimation-Quantization 3-D Geometry Coding Using Normal Meshes," *Digital Compression Conference*, March 2003.

PETER G. BINEV

IMI-Department of Mathematics,
University of South Carolina, Columbia, SC 29208
Email: binev@math.sc.edu

Research Interests

Numerical Analysis and Scientific Computing, Nonlinear Approximation Theory, Learning Theory, Image and Surface Processing, Multiscale and Sparse Data Representation

Education

Ph.D.	1985	Mathematics	University of Sofia
M.Sc.	1980	Mathematics	University of Sofia

Appointments

2000-Present	Research Associate Professor, Dept. of Mathematics, Univ. of South Carolina
1993-2006	Associate Professor, Faculty of Mathematics and Informatics, Univ. of Sofia
1999 (Spring)	Visiting Lecturer, Dept. of Mathematics, University of South Florida
1997 (Fall)	Visiting Lecturer, School of Computing & Mathematical Sciences, Univ. of Greenwich
1995 (Fall)	Visiting Professor, Dept. of Mathematics, University of Duisburg
1991-92	Research Fellow, Dept. of Mathematics, University of Duisburg
1990 (Fall)	Visiting Lecturer, Dept. of Mathematics, University of South Florida
1986 (Fall)	Research Fellow, Dept. of Theory of Functions, Steklov Mathematical Inst., Moscow
1984-93	Assistant Professor, Faculty of Mathematics and Informatics, Univ. of Sofia
1981-84	Research Fellow, Dept. of Mathematics, University of Sofia

Honors

Member, Special Bulgarian Awarding Committee in Computer Science and Applied Mathematics, 1998-2004; Member, Ruling Body of the Scientific Fund of the University of Sofia, 1997-2003; Head, Masters Program in Computer Graphics, University of Sofia, 1995-2002; Member, Scientific Committee in Mathematics and Mechanics, Bulgarian National Science Fund, 1998-1999; Fellowship from a TEMPUS program, University of Greenwich, UK, Fall 1997; Habilitation for an Associate Professor position at the University of Sofia, June 1993; DAAD Fellowship, University of Duisburg, Germany, January 1991 – February 1992; Rector's Award for the Best Young Scientist of the Year, University of Sofia, Bulgaria, 1989; Research Fellowship, Steklov Mathematical Institute, Moscow, Russia, September – December 1986; Graduate Scholarship, University of Sofia, 1981-1984; First Prize of Mathematical Balkaniade (University Students Mathematics Competition), Belgrade, Yugoslavia, 1977

Total Number of Refereed Publications:	19
Books:	1
Review Articles:	---

Selected Publications

P. Binev, A. Cohen, W. Dahmen, and R. DeVore, Universal Algorithms for Learning Theory – Part II: piecewise polynomial functions, *Constructive Approximation* (2007), to appear.

P. Binev, A. Cohen, W. Dahmen, R. DeVore, and V. Temlyakov, Universal algorithms for learning theory – Part I: piecewise constant functions, *Journal of Machine Learning Research* **6** (2005) 1297–1321.

P. Binev, W. Dahmen, R. DeVore, and N. Dyn, Adaptive Approximation of Curves, *Approximation Theory: A volume dedicated to Borislav Bojanov* (D.K. Dimitrov, G. Nikolov, and R. Uluchev, Eds.), Marin Drinov Academic Publishing House, Sofia (2004), 43-57.

P. Binev and R. DeVore, Fast Computation in Adaptive Tree Approximation, *Numer. Math.* **97** (2004), 193-217.

P. Binev, W. Dahmen, and R. DeVore, Adaptive Finite Element Methods with Convergence Rates, *Numer. Math.* **97** (2004), 219-268.

P. Binev, W. Dahmen, R. DeVore, and P. Petrushev, Approximation Classes for Adaptive Methods, *Serdica Math. J.* **28** (2002), 391-416.

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Research Interests

Approximation theory, harmonic analysis, differential equations, learning and image processing

Education

Ph.D.	1967	Mathematics	Ohio State University
B.S.	1964	Mathematics	Eastern Michigan University

Appointments

2005-present	Sumwalt Distinguished Professor Emeritus, University of South Carolina, Columbia, SC
2005-2006	Texas Instruments Professor, Electrical & Computer Engineering, Rice University, Houston, TX
1999-2005	Founding Director, Industrial Mathematics Inst., University of South Carolina, Columbia, SC
1986-2005	Sumwalt Professor of Mathematics, University of South Carolina, Columbia, SC
1977-1986	Professor, Mathematics Department, University of South Carolina, Columbia, SC
1974-1977	Professor, Mathematics Department, Oakland University, Oakland, CA
1970-1974	Associate Professor, Mathematics Department, Oakland University, Oakland, CA
1968-1970	Assistant Professor, Mathematics Department, Oakland University, Oakland, CA

Honors

Plenary Speaker at the International Congress of Mathematicians, Madrid (2006)
Honorary Doctorate, RWTH Aachen (2004)
Elected American Academy of Arts and Sciences Fellow (2001)
Alexander von Humboldt Prize (2002)
Gold Medal of Science, Sofia University (2001)
NDEA Fellow (1964-1967)
Alexander von Humboldt Fellowship (1975-1976)
Invited Addresses: AMS (1990), SIAM (1992), CMS (1994), FoCM (1999), SIAM (2000)

Professional Societies

American Mathematical Society
Society of Industrial and Applied Mathematics
IEEE

Total Number of Refereed Publications:	136
Books:	3
Review Articles:	2

Selected Publications

A. Cohen, W. Dahmen, and R. DeVore, "Compressed sensing and best k-term approximation," preprint.

P. Binev, R. DeVore, M. Heilsberg, S. Johnson, B. Karaivanov, B. Lane, and R. Sharpley, "Geometric modeling and encoding of terrains," preprint.

P. Binev, A. Cohen, W. Dahmen., R. DeVore, and V. Temlyakov, "Universal Algorithms for Learning Theory, Part I: piecewise constant functions," *Journal of Machine Learning Research* (JMLR), **6** (2005), 1297-1321.

R. DeVore, G. Kerkyacharian, D. Picard, V. Temlyakov, "On Mathematical Methods for Supervised Learning," *J. FoCM* **6** (2006), 3-58.

P. Binev and R. DeVore, "Fast computation in tree approximation," *Numerische Mathematik* **97** (2004), 193-217.

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Department of Electrical Engineering
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Research Interests

Statistical pattern recognition, nonparametric estimation, machine learning, information theory, wireless sensor networks, adaptive/hybrid systems, signal/image/video processing

Education

Ph.D.	1991	Electrical Engineering	M.I.T.
M.S.	1985	Electrical Engineering	Stanford University
M.S.	1985	Mathematics	Clarkson University
B.S.	1983, 1984	Mathematics, E.E.	Clarkson University

Appointments

2004-present	Professor, Dept. of Electrical Engineering, Princeton University, Princeton, NJ
2004-present	Master, Butler College, Princeton University, Princeton, NJ
2003-2005	Associate Dean, School of Engineering and Applied Science, Princeton University
1997-2004	Associate Professor, Dept. of Electrical Engineering, Princeton University, Princeton, NJ
2001	Visiting Researcher, Flarion Technologies, Bedminster, NJ
1997-2001	Consultant, Susquehanna International Group, Bala Cynwyd, PA
1991-1997	Assistant Professor, Dept. of Electrical Engineering, Princeton University, Princeton, NJ
1985-1991	Member of Technical Staff, MIT Lincoln Laboratory, Cambridge, MA

Honors

IEEE Fellow (2004)
SEAS Distinguished Teaching Award (2004)
NSF Young Investigator Award (1994)
ARO Young Investigator Award (1992)

Professional Societies

IEEE

Total Number of Refereed Publications:	65 (journal), 100 (conference)
Books:	1 (to be published Jan. 2007)
Review Articles:	2

Selected Publications

J.B. Predd, S.R. Kulkarni, H.V. Poor, "Distributed Learning in Wireless Sensor Networks," *IEEE Signal Processing Magazine*, **23**, No. 4, July (2006), 56-69.

H. Cai, S.R. Kulkarni, S. Verdu, "Universal Entropy Estimation Via Block Sorting," *IEEE Transactions on Information Theory*, **50**, No. 7, July (2004), 1551-1561.

S.R. Kulkarni, P. Viswanath, "A Deterministic Approach to Throughput Scaling in Wireless Networks," *IEEE Transactions on Information Theory*, **50**, No. 6, June (2004), 1041-1049.

S.R. Kulkarni, S. Sandilya, S.E. Posner, "Data-dependent k_n-Nearest Neighbor Estimators Consistent for Arbitrary Processes," *IEEE Transactions on Information Theory*, **48**, No. 10, Oct. (2002), 2785-2788.

P. Bartlett, S. Ben-David, S.R. Kulkarni, "Learning Changing Concepts by Exploiting the Structure of Change," *Machine Learning*, **41**, Nov. (2000), 153-174.

ANDREW J. KURDILA

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Research Interests

Dynamical system theory, Applied mathematics, Unmanned systems and robotics, Multibody dynamics simulation, Control theory and practice, Vibrations and smart structures, Modal testing and parameter estimation, Model updating of finite elements, Computational vibration problems, Vibration suppression of structures (both active and passive)

Education

Ph.D	1989	Engineering Science and Mechanics	Georgia Institute of Technology
M.S.	1985	Engineering Mechanics	University of Texas at Austin
B.S.	1983	Engineering Mechanics	University of Cincinnati

Appointments

08/05 - present	*W. Martin Johnson Professor*, Virginia Tech
1997 - 2005	Full Professor, University of Florida
1996 - 1997	Associate Professor, University of Florida
1993 - 1996	Associate Professor, Texas A&M University
1989 - 1993	Assistant Professor, Texas A&M University
1984 - 1985	Research Engineer, Structural Dynamics Research

Honors

W. Martin Johnson Professor of Mechanical Engineering, Virginia Tech, 2005
Associate Fellow, *American Institute Aeronautics and Astronautics*, 2002
Raymond L. Bisplinghoff Award, University of Florida, 1999 for Excellence in Teaching
TEES Faculty Fellow, Texas A&M University, September, 1999
Select Young Faculty Fellow, Texas A&M University, September, 1994
Luther Long Memorial Award, Georgia Institute of Technology, June, 1988.
Presidential Fellow, Georgia Institute of Technology, September, 1985-1989

Total Number of Refereed Publications: 70
Books: 2
Review Articles: 60

Selected Publications

Prazenica, R.J., Kurdila, A.J., Sharpley, R., and Evers, J., "Vision-Based Geometry Estimation and Receding Horizon Path Planning for UAVs Operating in Urban Environments," invited paper submitted to the special session on Vision-Based Control of Autonomous Aerial Vehicles, *American Control Conference*, June 2006.

Prazenica, R.J., Kurdila, A.J., Sharpley, R., and Evers, J., "Multiresolution and Adaptive Path Planning for Maneuver of Micro-Air-Vehicles in Urban Environments," invited paper in the special session on Vision-Based Control, *AIAA Guidance, Navigation, and Control Conference*, San Francisco, CA, August 2005.

Watkins, A., Prazenica, R.J., Kurdila, A.J., and Wiens, G., "Vision-Based Receding Horizon Control for a Wheeled Mobile Robot in an Urban Environment," *AIAA Guidance, Navigation, and Control Conference*, San Francisco, CA, August 2005.

Webb, T., Prazenica, R.J., Kurdila, A.J., and Lind, R., "Vision-Based State Estimation for Uninhabited Aerial Vehicles," *AIAA Guidance, Navigation, and Control Conference*, San Francisco, CA, August 2005.

Kurdila, A., Nechyba, M., Prazenica, R., Dahmen, W., Binev, P., DeVore, R., and Sharpley, R., "Vision-Based Control of Micro-Air-Vehicles: Progress and Problems in Estimation," *43rd IEEE Conference on Decision and Control*, Paradise Island, Bahamas, December 2004, also in review by *IEEE Transactions on Aerospace Systems*.

STANLEY J. OSHER

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Research Interests

Scientific Computing, Numerical Analysis, Applied Partial Differential Equations

Education

1966	New York University, Ph.D., (J.T. Schwartz, thesis advisor)
1964	New York University, M.S.
1962	Brooklyn College, B.S.

Appointments

1977 – Present	Professor, Department of Mathematics, UCLA
1975 – 1977	Professor, Department of Mathematics, SUNY, Stony Brook
1970 – 1975	Associate Professor, Department of Mathematics, SUNY, Stony Brook
1968 – 1970	Assistant Professor, Department of Mathematics, University of California Berkeley
1966 – 1968	Assistant-Associate Mathematician, Brookhaven National Laboratories

Honors

Fulbright Fellow, 1971; Alfred P. Sloan Fellow, 1972-1974; SERC Fellowship (England), 1982; US-Israel BSF Fellow, 1986; NASA Public Service Group Achievement Award, 1992; Invited speaker, International Congress of Mathematicians, Zurich, 1994; ICI Original Highly Cited Researcher, 2002; Japan Society of Mechanical Engineers Computational Mechanics Award, 2003; ICIAM Pioneer Prize, 2003; Elected to US National Academy of Science, 2005; SIAM Ralph E. Kleinman Prize

Professional Activities

- Coinventor and a principle developer of widely used i) state-of-the-art high resolution schemes for approximating hyperbolic conservation laws and Hamilton-Jacobi equations; ii) level set methods for computing moving fronts involving topological changes; applications and extensions include a variational version, multiphase flow, crystal growth, computer vision and graphics; iii) total variation and other partial differential equations based image processing techniques.
- Associate Editor of the Journal of Computational Physics, Mathematics of Computation, SIAM Journal on Numerical Analysis and 7 other journals. Co-organizer of several long meetings and Director of Special Projects at the new NSF funded Institute of Pure and Applied Mathematics at UCLA.

Selected Publications

S.J. Osher, J.A. Sethian, "Fronts propagating with curvature dependent speed. Algorithms based on Hamilton-Jacobi formulations," *J. Comp. Phys*. **79** (1988) 12-49.

S.J. Osher and L. Rudin, "Feature oriented image enhancement using shock filters," *SIAM J. Num. Anal.* **28**, (1990) 919-940.

S.J. Osher and C.-W. Shu, "High order essentially nonoscillatory schemes for Hamilton-Jacobi Equations," *SIAM J. Num. Anal*. **28** (1991) 907-922.

H.K. Zhao, T. Chan, B. Merriman and S.J. Osher, "A variational level set approach to multi-phase motion," *J. Comp. Phys*., **115** (1996) 179-195.

L. Rudin, S.J. Osher and E. Fatemi, "Nonlinear total variation based noise removal algorithms," *Physica D* **60** (1992) 259-268.

MARK A. PIERSON

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Virginia Polytechnic Institute and State University, Blacksburg, VA 24061
Email: mark.pierson@vt.edu

Research Interests

Applied mathematics, abstract differential-algebraic equations (DAEs), theory of partial differential equations, semigroup theory, numerical analysis, dynamical system theory, unmanned systems and robotics, morphing-wing micro-aerial vehicles, optimal control theory, adaptive control, learning theory, artificial neural networks, pattern recognition

Education

Ph.D	2005	Mathematics	Virginia Tech
M.S.	2000	Mathematics	Virginia Tech
B.A.	1978	German	University of California, Davis

Appointments

11/06 - present	Research Associate Professor, Mechanical Engineering, Virginia Tech
05/05 - present	Adjunct Professor, Mathematics, Virginia Tech
09/05 - present	JOUSTER Research Project Manager, Mechanical Engineering, Virginia Tech
06/05 – 09/05	DUSEL Research Project Manager, Research Division, Virginia Tech
08/01 – 05/05	Graduate Teaching Asst. / Research Asst., Mathematics, Virginia Tech
1978 - 2001	Naval Officer, U.S. Navy, nuclear submarines
1998 – 2001	Deputy Head, Engineering, Materials & Physical Sciences Department, Office of Naval Research

Honors

Phi Kappa Phi, All-disciplines Honor Society, 2004
Pi Mu Epsilon, Mathematics Honor Society, 2003
Beta Gamma Sigma, Business and Management Honor Society, 1992

Professional Societies

Society for Industrial and Applied Mathematics (SIAM)
Activity Groups: Dynamical Systems; Control and Systems Theory; Analysis of Partial Differential Equations
American Mathematical Society (AMS)
Association for Unmanned Vehicle Systems International (AUVSI)

Total Number of Refereed Publications:	---
Books:	1 (in preparation)
Review Articles:	1

Selected Publications

Pierson, M. A., Kurdila, A. J., "Qualitative Design of Micro-Aerial Vehicles (MAVs)," Proceedings of *AUVSI's Unmanned Systems North America 2006 Conference*, Orlando, FL, August 2006.

Pierson, M. A., Cliff, E. M., Herdman, T. L., "Introduction to Partial Differential-Algebraic Equations," *Joint American Mathematical Society/Mathematics Association of America Mathematics Meeting*, Atlanta, GA, January 2005.

Pierson, M. A., Cliff, E. M., Herdman, T. L., "Introduction to Abstract Differential-Algebraic Equations," *Society for Industrial and Applied Mathematics (SIAM) Conference on Analysis of Partial Differential Equations*, Houston, TX, December 2004.

Pierson, M. A., Cliff, E. M., Herdman, T. L., "An Introduction to Abstract Differential-Algebraic Equations With an Emphasis on DAE Theory for Two Coupled Beams," *Southeastern-Atlantic Regional Conference on Differential Equations*, Chattanooga, TN, October, 2004.

GUERGANA PETROVA

Department of Mathematics,
Texas A&M University, College Station, TX 77843-3368
Email: gpetrova@math.tamu.edu

Research Interests

Differential equations, Numerical analysis, Approximation theory

Education

Ph.D.	1999	Mathematics	University of South Carolina (Thesis Advisor: R. A. DeVore)
M.S.	1993	Mathematics	Sofia University, Sofia, Bulgaria
B.A.	1991	Mathematics	Sofia University, Sofia, Bulgaria

Appointments

2006 – present	Associate Professor, Department of Mathematics, Texas A&M University
2001 – 2006	Assistant Professor, Department of Mathematics, Texas A&M University
1999 – 2001	Visiting Assistant Professor, Department of Mathematics, University of Michigan

Professional Societies

American Mathematical Society
Society of Industrial and Applied Mathematics
Association for Women in Mathematics

Total Number of Refereed Publications:	24
Books:	---
Review Articles:	---

Selected Publications

R. DeVore, G. Petrova, and V. Temlyakov, "Best Basis Selection for Approximation in L_p," *J. FoCM* **3** (2003), 161-185.

A. Kurganov, S. Noelle, and G. Petrova, "Semi-discrete central-upwind schemes for hyperbolic conservation laws and Hamilton-Jacobi equations," *SIAM J. Sci. Comput.* **23** (2001), 707-740.

P. Bechler, R. DeVore, A. Kamont, G. Petrova, and P. Wojtasczyk, "Greedy wavelet projections are bounded on BV," *Trans. Amer. Math. Soc*., to appear.

R. DeVore, G. Petrova, and P. Wojtasczyk, "Anisotropic Smoothness Spaces via Level Sets," preprint.

R. DeVore and G. Petrova, "The averaging lemma," *J. Amer. Math. Soc.* **14** (2001), 279-296.

MICHAEL J. ROAN

141 Durham Hall, Department of Mechanical Engineering
Virginia Polytechnic Institute and State University, Blacksburg, VA 24061
Email: mroan@vt.edu

Research Interests

Information Fusion, Information Integration for Heterogeneous Systems, Signal Processing for Sensor Networks, Underwater Acoustics, Acoustical Signal Processing, Automated Health Monitoring for Rotating Machinery, Sensor Development for Chemical, Biological, and Explosives Detection

Education

Ph.D.	1999	Acoustics	Pennsylvania State University
M.S.	1993	Acoustics	Pennsylvania State University
B.A.	1990	Physics	Pennsylvania State University

Appointments

08/2005 - present	Associate Professor, Mechanical Engineering Department, Virginia Polytechnic Institute and State University
08/2004 - 08/2005	Visiting Fellow, Electrical Engineering, Princeton University
03/1996 - 08/2005	Signal Processing Department Head, Autonomous Control and Intelligent Systems Division, Applied Research Laboratory, Pennsylvania State University
02/1995 - 03/1996	Systems Engineer, Alliant Techsystems/Westinghouse Electronic Systems Group, Baltimore, MD
08/1993 - 02/1995	Engineer, Noise Cancellation Technologies, Linthicum, MD

Honors

Office of Naval Research Young Investigator Award, 2004

Professional Societies

Member of the IEEE
Member of the Acoustical Society of America

Total Number of Refereed Publications:	21
Books:	0
Review Articles:	0

Selected Publications

J. G. Erling, M.J. Roan, and M.G. Gramann, "Performance Bounds for Multi-Source Parameter Estimation Using a Multi-Array Network," *IEEE Transactions on Signal Processing* (To Appear)

L.H.Sibul, M.J., Roan, S.C., Schwartz, and C., Coviello, "Lossless Information Integration in Multistatic Active Detection Systems," *IEEE Transactions Signal Processing, October 2006.*

M.J. Roan, M.G. Gramann, J. G. Erling, and L.H. Sibul, "Nonlinear Adaptive Signal Processing in Experimental Acoustics," *The Journal of the Acoustical Society of America*, October, 2003.

M.J. Roan, "Artificial Target Discrimination Using Weapon-Platform Connectivity as an Enabling Technology," *U.S. Navy Journal of Underwater Acoustics*, Special Issue on Remote Sensing Technology, April 2002.

M.J. Roan, J.G. Erling, and M. G. Gramann, "Blind Deconvolution for Horizontal Multipath Removal – An Angle Space Pre-Filter," *U.S. Navy Journal of Underwater Acoustics*, Special Issue on Remote Sensing Technology, April 2002.

M.J. Roan, L.H. Sibul and J.J. Rokita, "Estimator-Correlator: A Wavelet Transform Domain Approach to Wideband Detection and Estimation," *U.S. Navy Journal of Underwater Acoustics* Special Issue on Undersea Signal Processing, January 2001.

ROBERT C. SHARPLEY

IMI-Department of Mathematics
University of South Carolina, Columbia, SC 29208
Email: sharpley@math.sc.edu

Research Interests

Multiresolution analysis and wavelets, Classical and numerical analysis, Partial differential equations and Fourier analysis, Computational science and mathematics, Geosciences: groundwater flow and transport

Education

Ph.D.	1972	Mathematics	University of Texas
M.A.	1969	Mathematics	University of Texas
B.A.	1968	Mathematics	University of Texas

Appointments

1983-Present	Professor, Department of Mathematics, University of South Carolina
1978-83	Associate Professor, Department of Mathematics, University of South Carolina
1976-78	Assistant Professor, Department of Mathematics, University of South Carolina
1972-76	Assistant Professor, Department of Mathematics, Oakland University, Rochester, MI

Visiting Appointments

1992	Institute for Scientific Computation, Texas A&M University, College Station, TX.
1986-87	University of Wyoming, Laramie, WY.
1978-79	McMaster University, Hamilton, Ontario.
1972 (Summer)	Louisiana State University, Baton Rouge, LA

Honors

Editorial Board, Constructive Approximation, 1990-2004; Member-at-Large, NSF-KDI Ideal Data Representation Center, 1998-present; Steering Committee, Groundwater Computational Grand Challenge, DOE/PICS, 1991-1997; State of South Carolina EPSCoR Committee, 1994-1998; State of South Carolina Supercomputer and Networking Board, 1995-1997.

Total Number of Refereed Publications:	51
Books:	2
Review Articles:	---

Selected Publications

P. Binev, R. DeVore, M. Heilsberg, S. Johnson, B. Karaivanov, B. Lane, and R. Sharpley, "Geometric modeling and encoding of terrains," preprint.

A. Kurdila, M. Nechyba, R. Lind, P. Ifju, P. Binev, W. Dahmen, R. DeVore, R. Sharpley, "Vision-Based Control of Micro-Air-Vehicles: Progress and Problems in Estimation," 43rd IEEE Conference on Decision and Control, Paradise Island, Bahamas, December 2004, p. 1636-1642. Also in review by IEEE Transactions on Aerospace Systems.

R.J. Prazenica, A.J. Kurdila, R.C. Sharpley and J. Evers, "Multiresolution and Adaptive Path Planning for Maneuver of Micro-Air-Vehicles in Urban Environments," invited paper in the special session on Vision-Based Control, AIAA Guidance, Navigation, and Control Conference, San Francisco, CA, August 2005.

R. DeVore, L.S. Johnson, C. Pan, and R. Sharpley, 'Optimal entropy encoders for mining multiply resolved data,' in "Data Mining II," (N. Ebecken, C.A. Brebbia, eds.), WIT Press, Boston, 2000, 73-82.

R.J. Prazenica, A.J. Kurdila, R.C. Sharpley and J. Evers, "Vision-Based Geometry Estimation and Receding Horizon Path Planning for UAVs Operating in Urban Environments," invited paper submitted to the special session on Vision-Based Control of Autonomous Aerial Vehicles, American Control Conference, June 2006.

YEN-HSI RICHARD TSAI

Department of Mathematics
University of Texas at Austin, Austin, TX 78712
Email: ytsai@math.utexas.edu

Research Interests

Multiscale problems and the related numerical methods; Level set methods and their applications related to high frequency wave propagation and free boundary problems; Path planning problems; Computer graphics/vision and image processing

Education

Ph.D.	2002	Mathematics	UCLA (Thesis Advisor: S. J. Osher)
M.A.	1999	Mathematics	UCLA
B.S.	1995	Mathematics	National Taiwan University, Taiwan

Appointments

2004-present	Assistant Professor, Mathematics Department and Institute for Computational Engineering and Sciences (ICES), University of Texas at Austin
2002-2004	Veblen Research Instructor, Joint employment of Princeton University and Institute for Advanced Study

Honors

Alfred P. Sloan Fellowship, 2006-2007
Visiting Fellowship of the Isaac Newton Institute for Mathematical Sciences, 2007
National Science Foundation Division of Mathematics Grant Award, 2005-2008
University of Texas Summer Research Appointment, 2005
Veblen Research Instructorship, Institute for Advanced Study and Princeton University, 2002-2004
The FEMLAB Prize, April 2002

Professional Societies

Alfred P. Sloan Fellow
Institute for Advanced Study
American Mathematics Society
Society of Industrial and Applied Mathematics

Total Number of Refereed Publications: 24
Books: ---
Review Articles: ---

Selected Publications

L.-T. Cheng, R. Tsai. "Visibility Optimizations using Variational Approaches," *Communications of Mathematical Sciences* **3** (2005).

Y. Landa, R. Tsai, and L.-T. Cheng. "Visibility of Point Clouds and Mapping of Unknown Environments," In J. Blanc-Talon et al., editors, ACIVS, LNCS 4179, pp.1014-1025, Springer-Verlag 2006.

Y.-H.R. Tsai, L.-T. Cheng, S. Osher, and P. Burchard, G. Sapiro, "Visibility and its dynamics in a PDE based implicit Framework," *Journal of Computational Physics* **199** (2004), 260-290.

Jin Hailin Anthony J. Yezzi, Yen-His Tsai, Li-Tien Cheng, and Stefano Soatto, "Estimation of 3D Surface Shape and Smooth Radiance from 2D Images: A Level Set Approach," *J. Scientific Computing* **19**, No. 1-3 (2003).

Chiu-Yen Kao and R. Tsai, "A Level Set Formulation for Visibility and Its Discretization," preprint.

HONGKAI ZHAO

Department of Mathematics & Department of Computer Science,
University of California, Irvine, CA 92697
Email: zhao@math.uci.edu

Research Interests

Numerical analysis and scientific computing, level set method, moving interface and free boundary problem, computer vision/graphics, inverse problem and imaging

Education

Ph.D.	6/1996	Mathematics	University of California, Los Angeles
M.S.	8/1992	Applied Mathematics	University of Southern California
B.S.	6/1990	Applied Mathematics	Beijing University, Beijing, P.R.China

Appointments

7/2004 - present	Associate Professor, Department of Computer Science, UC, Irvine
7/2003 - present	Associate Professor, Department of Mathematics, UC, Irvine
7/1999 - 6/2003	Assistant Professor, Department of Mathematics, UC, Irvine
9/1996 - 9/1999	Gabor Szego Assistant Professor, Department of Mathematics, Stanford University

Honors

Alfred P. Sloan Research Fellow, 2002-2004.
UCI Faculty Career Development Award, 1999-2000.

Professional Societies

American Mathematical Society
Society of Industrial and Applied Mathematics

Total Number of Refereed Publications:	28
Books:	---
Review Articles:	---

Selected Publications

D. Lu, H. Zhao, M. Jiang, S. Zhou, and T. Zhou, "A Surface Reconstruction Method for Highly Noisy Point Clouds," to appear in *Lecture Notes in Computer Science*, Springer.

S. Hou, K. Solna, H. Zhao, "A Direct Imaging Algorithm For Extended Targets," *Inverse Problem* **22** (2006), 1151-1178.

H. K. Zhao, "Fast Sweeping Method for Eikonal Equations," *Mathematics of Computation* **74**, (2005), 603-627.

H. K. Zhao, S. Osher, R. Fedkiw, "Fast Surface Reconstruction Using the Level Set Method," *Proceedings of IEEE Workshop on Variational and Level Set Methods in Computer Vision* (VLSM 2001), July, 2001.

H. K. Zhao, S. Osher, B. Merriman, M. Kang, "Implicit and Non-parametric Shape Reconstruction from Unorganized Points Using Variational Level Set Method," *Computer Vision and Image Understanding*, **80** (2000), 295-319.

RICE

OFFICE OF SPONSORED RESEARCH

November 3, 2006

Etheredge Steve
Director of the Office of Sponsored Projects
The University of South Carolina
901 Sumter Street
Columbia, SC 29208

Dear Mr. Etheredge:

Rice University is pleased to be included in the application to Army Research Office for a research project entitled "Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data" under the direction of Professor Ronald A. DeVore, Department of Mathematics, the University of South Carolina.

Research to be subcontracted to Rice University will be carried out under the direction of Dr. Richard G. Baraniuk, Department of Electrical and Computer Engineering. The sum of $665,000, including facilities and administrative costs, is requested for the period May 1, 2007 through April 30, 2012.

Sincerely,

Henn Langberg

Grant Coordinator
Rice University, Office of Sponsored Research MS-16
P.O. Box 1892
Houston, Texas 77251-1892
Phone:713-348-5584
Fax: 713-348-5425
E-mail: henn@rice.edu

TEXAS A&M RESEARCH FOUNDATION
979-845-8600 979-862-3250 FAX
http://rf-web.tamu.edu

November 2, 2006

Ms. Lumi Bakos
Grant Administrator
5th Floor Byrnes Building
901 Sumter St
Columbia, SC 29208

Reference: 0700337
"Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data"

The enclosed proposal is submitted for your consideration.

The Principal Investigator, Dr. Guergana Petrova, will be pleased to offer additional technical or scientific detail and may be reached at 979-845-5298 or gpetrova@math.tamu.edu. Please contact Ms. Marcie Avery (979-845-8658 or award@rf-mail.tamu.edu), Senior Research Administrator and Negotiator, for fiscal or administrative information.

Sincerely,

Jane Zuber
Associate Vice President

JZ:slp
Enclosures

cc: Dr. Guergana Petrova

3578 TAMU UNIVERSITY DRIVE AND WELLBORN ROAD COLLEGE STATION, TEXAS 77843

APPLICATION FOR FEDERAL ASSISTANCE

Version 7/03

2. DATE SUBMITTED		Applicant Identifier Petrova 0700337
3. DATE RECEIVED BY STATE		State Application Identifier
4. DATE RECEIVED BY FEDERAL AGENCY		Federal Identifier

1. TYPE OF SUBMISSION:

Application	Pre-application
☐ Construction	☐ Construction
☑ Non-Construction	☐ Non-Construction

5. APPLICANT INFORMATION

Legal Name: Texas A&M Research Foundation	**Organizational Unit:** Department:
Organizational DUNS: 07-859-2789	Division:
Address: Street: 3578 TAMU	**Name and telephone number of person to be contacted on matters involving this application (give area code)** Prefix: / First Name: Marcie
City: College Station	Middle Name
County: Brazos	Last Name Avery
State: TX / Zip Code: 77843-3578	Suffix:
Country: United States	Email: award@rf-mail.tamu.edu
6. EMPLOYER IDENTIFICATION NUMBER *(EIN)*: 74-1238434	Phone Number (give area code): 979-845-8658 Fax Number (give area code): 979-862-3250

8. TYPE OF APPLICATION:

☑ New ☐ Continuation ☐ Revision

If Revision, enter appropriate letter(s) in box(es)
(See back of form for description of letters.) ☐ ☐

Other (specify)

7. TYPE OF APPLICANT: (See back of form for Application Types)

Other

Other (specify)
Non-Profit Affiliated with Educational Inst

9. NAME OF FEDERAL AGENCY:
University of South Carolina (Dept. of Army)

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: 12-431

TITLE (Name of Program):
Basic Scientific Research

11. DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:
Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data

12. AREAS AFFECTED BY PROJECT *(Cities, Counties, States, etc.)*:
United States

13. PROPOSED PROJECT

Start Date:	Ending Date:
05/01/2007	04/30/2012

14. CONGRESSIONAL DISTRICTS OF:

a. Applicant	b. Project
17	17

15. ESTIMATED FUNDING:

a. Federal	$ 27,917 .00
b. Applicant	$ .00
c. State	$ .00
d. Local	$ .00
e. Other	$ .00
f. Program Income	$ .00
g. TOTAL	$ 27,917 .00

16. IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. Yes. ☐ THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON

DATE:

b. No. ☑ PROGRAM IS NOT COVERED BY E. O. 12372

☐ OR PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. IS THE APPLICANT DELINQUENT ON ANY FEDERAL DEBT?

☐ Yes If "Yes" attach an explanation. ☑ No

18. TO THE BEST OF MY KNOWLEDGE AND BELIEF, ALL DATA IN THIS APPLICATION/PREAPPLICATION ARE TRUE AND CORRECT. THE DOCUMENT HAS BEEN DULY AUTHORIZED BY THE GOVERNING BODY OF THE APPLICANT AND THE APPLICANT WILL COMPLY WITH THE ATTACHED ASSURANCES IF THE ASSISTANCE IS AWARDED.

a. Authorized Representative

Prefix Ms.	First Name Jane	Middle Name
Last Name Zuber		Suffix
b. Title Associate Vice President		c. Telephone Number (give area code) 979-845-8658
d. Signature of Authorized Representative Jane Zuber		e. Date Signed 11.3.06

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Prescribed by OMB Circular A-102

OFFICE OF SPONSORED PROJECTS
THE UNIVERSITY OF TEXAS AT AUSTIN

P.O. Box 7726 • Austin, Texas 78713-7726 • (512) 471-6424 • Fax: (512) 471-6564 • (mc A9000)

November 9, 2006

University of South Carolina
ATTN: Ms. Lumi Bakos
901 Sumter Street
Columbia, S.C. 29208

RE: "Model Classes, Approximation and Metrices for Dynamic Processing of Urban Terrain Data, OSP#200602472-001."

Dear Ms. Bakos:

We are pleased to submit a proposal prepared by Dr. Yen-Hsi Tsai of our Institute for Computational Engineering and Sciences. This application has the approval of cognizant officials of The University of Texas at Austin.

For information relating to the technical portions of this project, you may contact Dr. Yen-Hsi Tsai, Institute for Computational Engineering and Sciences, The University of Texas at Austin. Contractual matters should be referred to Margaret Hoard, Office of Sponsored Projects, The University of Texas at Austin, Post Office Box 7726, Austin, TX 78713-7726 (Phone: 512/471-6288).

Awards and post-award matters should be referred to the Office of Sponsored Projects, ATTN: Awards Dept (Phone: 512/471-6424 or E-mail: osp@mail.utexas.edu).

Sincerely,

Susan Wyatt Sedwick, Ph.D., C.R.A.
Associate Vice President for Research
Director, Office of Sponsored Projects

SWS:slm

Enclosure

UNIVERSITY OF CALIFORNIA, IRVINE

BERKELEY · DAVIS · IRVINE · LOS ANGELES · MERCED · RIVERSIDE · SAN DIEGO · SAN FRANCISCO · SANTA BARBARA · SANTA CRUZ

OFFICE OF RESEARCH ADMINISTRATION

300 University Tower
Irvine, CA 92697-7600
(949) 824-4768
Fax (949) 824-2094
http://www.rgs.uci.edu/

Express Mail to:
4199 Campus Dr.
Suite 300, University Tower
Irvine, CA 92612

November 6, 2006

Lumi Bakos
Sponsored Awards Management
901 Sumter Street
University of South Carolina
Columbia, SC 92908

RE: UCI Proposal Number 41144

On behalf of The Regents of the University of California, we are presenting for your review a request for support of the following proposal:

Principal Investigator:	Dr. Hongkai Zhao Department of Mathematics
Title:	"Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data"
Support Requested:	$623,365
Period of Support:	05/01/07 – 04/30/12
Type of Request:	New Research Subcontract

Your favorable consideration will be greatly appreciated. If additional information is required, please contact the undersigned at (949) 824-8109.

Sincerely,

Lesley Dowd
Senior Contract and Grant Officer

UNIVERSITY OF CALIFORNIA, LOS ANGELES **UCLA**

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

OFFICE OF CONTRACT AND GRANT ADMINISTRATION
10920 WILSHIRE BOULEVARD, SUITE 1200
LOS ANGELES, CALIFORNIA 90024-1406

PHONE: (310) 794-0102
FAX: (310) 794-0631

www.research.ucla.edu/ocga

November 3, 2006

Ms. Lumi Bakos
Sponsored Awards Management
901 Sumter Street
Columbia, SC 29208

Attention: Dr. Ronald DeVores, Department of Mathematics

On behalf of the The Regents of the University of California, Los Angeles Campus, I am pleased to submit the following proposal in response to ONR BAA06-028.

Title:	"Model Classes, Approximation, and Metrics for Dynamic Processing Urban Terrain Data "
Period of Performance:	May 1, 2007 – April 30, 2012
Amount Requested:	$750,000. 3 Year Basic Effort, 2 Year Option
Principal Investigator:	Professor Stanley Osher, Department of Mathematics

We understand that the University of South Carolina will be the applicant organization to the BAA referenced above and that The Regents of the University of California Los Angeles campus will be a subawardee.

If awarded it should be issued to *The Regents of the University of California* and forwarded to this office. Please contact Ms Evelyn Leon, Department Contract & Grant Administrator at (310) 825-8534 or eleon@math.ucla.edu for any questions concerning the budget. Question concerning contractual and administrative matters should be addressed to me at (310) 794-0179 or bharris-holdrege@resadmin.ucla.edu.

Sincerely,

Barbara J. Harris-Holdrege
Contract and Grant Officer

Princeton University **Office of Research and Project Administration**
Fourth Floor, New South Building
Post Office Box 36
Princeton, New Jersey 08544-0036
FAX: 609-258-1159

Michelle D. Christy
Director
Phone: 609-258-3090
Email: mchristy@princeton.edu

November 9, 2006

Ms. Lumi Bakos, Administrator
Sponsored Awards Management
University of South Carolina
901 Sumter Street
Columbia, SC 29208

Subject: Research Proposal Entitled, "Distributed Learning and Pattern Recognition for Terrain Modeling and Analysis" Professor Sanjeev Kulkarni Princeton University Principal Investigators

Dear Ms. Bakos:

Princeton is pleased to submit the subject proposal in response to Broad Agency Announcement 06-028. Princeton anticipates a three year period of performance beginning May 1, 2007 funded at $210,000 and a two year optional period beginning May 1, 2010 funded at $140,000. for a total of $350,000. as detailed in our budget.

At this time I would like to point out that Princeton is a nonprofit educational institution, which conducts fundamental research in basic and applied science and engineering that is widely and openly published and made available to the scientific and academic community.

Princeton shall enter into agreements for the support of research or instruction that do not require it, as a university, to participate in (1) handling or transmitting classified information, documents, material, or equipment, or (2) processing the security clearance of any person or facility, or (3) controlling access to any information in accordance with any security regulation whether public or private.

Princeton University should be identified in any resulting contractual documents as "The Trustees of Princeton University."

Thank you for your consideration of this proposal. Should you require additional information, please feel free to contact me.

Sincerely,

Michelle D. Christy

Michelle D. Christy

VirginiaTech

Office of Sponsored Programs
460 Turner Street, Suite 306
Blacksburg, Virginia 24060
Phone: (540) 231-5281 Fax: (540) 231-3599
E-mail:
www.osp.vt.edu

November 7, 2006

Ms. Lumi Bakos
University of South Carolina
Sponsored Awards Management
901 Sumter Street
Columbia, SC 29208

Dear Ms. Bakos:

Please find enclosed a research proposal entitled, "Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data". This proposal is being submitted by Andrew Kurdila, Mark Pierson, and Michael Roan in our Department of Mechanical Engineering.

All correspondence related to this proposal should reference Proposal Number 07-0908-11.

The enclosed information relating to an application for funding of a program is confidential and for use by the funding agency only. It may be distributed only to those persons whose evaluation is required to determine if the proposed research merits approval and funding by the agency. It is understood that other parties may have access for purposes as specified under 5 USC 552(a).

Access to the general public of the information enclosed herewith is prohibited until notice has been received of the name and affiliation of the requestor, and the purpose of the request. The investigator and Virginia Tech shall be allowed sufficient time to review the application and to redact those portions considered to be confidential. In the event that the funding agency disagrees with the request for redaction made by the investigator and/or Virginia Tech, the investigator and/or Virginia Tech reserves the right of appeal prior to release of the enclosed confidential information.

The University appreciates the opportunity to submit this proposal. If questions or a budgetary or fiscal nature arise, please contact Mr. Travis Hundley at (540)231-9168. Questions of a technical nature should be addressed to the principal investigator.

Sincerely,

David W. Richardson
Assistant VP for OSP Administration

smb
Enclosures
Cc:
A. Kurdila
M. Pierson
M. Roan
K. Ball
E. Henneke
University File

Submitted in response to FY 2007 DoD MURI Initiative BAA

TECHNICAL PROPOSAL COVER

BAA NUMBER: 06-028

1. PRINCIPAL INVESTIGATOR

Dr.	Andrew	J.	Kurdila	Andrew J. Kurdila
(Title)	(First Name)	(MI)	(Last Name)	PI Signature (please use blue ink)

(540) 231-8028	(540) 231-9100	kurdila@vt.edu
(Phone Number)	(FAX Number)	(Email Address)

Virginia Polytechnic Institute and State University / Mechanical. Engineering. Dept.
(Institution/Department/Division)

Office of Sponsored Programs, 460 Turner Street, Suite 306
(Street/PO Box/Building)

Blacksburg	Virginia	24061
(City)	(State)	(Zip Code)

CURRENT DoD CONTRACTOR OR GRANTEE: YES_X_NO____

If yes, give Agency, Point of Contact, Phone Number: U.S. Army RDECOM STTC, JOUSTER Program Manager, Mr. Irwin Hudson, (407) 384-5544, and AFOSR/Eglin A.F.B., AVCAAF Program Manager, Maj. Todd Combs, phone (703) 696-9548.

2. PROPOSAL:

Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data
(Title: be brief and descriptive; do not use acronyms or mathematical or scientific notation)

1 May 2007 to 30 APR 2010	1 MAY 2010 to 30 APR 2012	
Proposed Base Period	Proposed Option Period	Your Institution's Proposal No.

Submitted to: ARO	#28	Dynamic Modeling of 3D Urban Terrain
DoD Agency	Topic #	Topic Title

Total funds requested from USC:

$390,000 +	$260,000 =	$650,000
3-year base total	2-year option total	5-year total

OTHER AGENCIES RECEIVING THIS RESEARCH FUNDING REQUEST
(e.g. NSF, DOE, NASA, NIH). Please identify agency(ies) and give Name(s) and Phone Number(s) of Point(s) of Contact at those agencies:

None

3. MINORITY INSTITUTION: ______Check here if the academic institution named above is qualified to be identified by the Department of Education as a minority institution (i.e., a historically Black college or university, Hispanic-serving institution, Tribal college or university, or other institution meeting statutorily-defined criteria for serving ethnic groups that are underrepresented in science and engineering). The Department of Education maintains the list of U.S. accredited postsecondary institutions that currently meet the statutory criteria for identification as minority institutions at the following web site: http://www.ed.gov/offices/OCR/minorityinst.html.

4. INSTITUTION: NAME AND ADDRESS OF UNIVERSITY OFFICIAL AUTHORIZED TO OBLIGATE CONTRACTUALLY AND WITH WHOM BUSINESS NEGOTIATIONS SHOULD BE CONDUCTED

Mr.	David	W.	Richardson
(Title)	(First Name)	(MI)	(Last Name)

(540) 231-5281	(540-231-3599)	daverich@vt.edu
(Phone Number)	(FAX Number)	(Email Address)

Virginia Polytechnic Institute and State University
(Name of Grantee (University)

Office of Sponsored Programs, 460 Turner Street, Suite 306
Street Address (P.O. Box Numbers Cannot Be Accepted)

Blacksburg	Virginia	24061
(City)	(State)	(Zip Code)

Taxpayer Identification No. (TIN) 54-6001805 DUNS No. 003137015

[signature] ______________________ 11/17/06
Signature of Authorized University Official Date
(Please use blue ink)

[1] The DoD is required by 31 U.S.C. 7701 to obtain each recipient's TIN (usually the Employer Identification Number) for purposes of collecting and reporting on any delinquent amounts that may arise out of the recipient's relationship with the Government.

[2] The institution's number in the data universal numbering system (DUNS) is a unique nine digit (all numeric) identification number for organizations. Dun and Bradstreet Corporation assigns it. You can receive a DUNS number by calling Dun & Bradstreet at 1(800) 333-0505 or go to the Dun & Bradstreet Web site at http://www.dnb.com/dnbhome.htm.

DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER WEAPONS DIVISION
1 ADMINISTRATION CIRCLE
CHINA LAKE, CA 93555-6100
575 I AVENUE SUITE 1
POINT MUGU, CA 93042-5049

IN REPLY REFER TO:
9980
498100D/041
1 Nov 06

From: Commander, Naval Air Warfare Center Weapons Division
To: Army Research Office, Information, Electronics and Surveillance, Code 31,
Attn: Dr. John Lavery , U. S. Army Research Office,
4300 S. Miami Blvd., Durham, NC 27703-9142

Subj: INTENTION OF NAWCWD TO SUPPORT RESEARCH INIATIVE

1. The purpose of this memorandum is to provide written documentation with regard to the Naval Air Warfare Center Weapons Division's (NAWCWD) willingness to support Professor Ron DeVore and his team members as part of their response to the Multidisciplinary University Research Initiative (MURI) Topic Number 28 "Dynamic Modeling of Urban Terrain," The mathematical capability of this team is truly exceptional. It is a team that both understands the topic and has created a significant mass of the fundamental mathematics associated with implicit methods. We have a long history of collaboration and interaction with members of the team, notably Professor DeVore at South Carolina, Professor Stan Osher at University of California, Los Angeles, and Professor Richard Baraniuk at Rice University.

2. Researchers at NAWCWD, China Lake, California have developed an excellent working relationship with investigators on the MURI team over the last several years. NAWCWD, DeVore, and Osher are all participants and collaborators on a current Defense Advanced Research Projects Agency (DARPA), program, "Geospatial Representation and Analysis," sponsored by Dr. Carey Schwartz. This topic is of significant interest to the Navy, and in particular to NAWCWD. China Lake already has significant activities underway in geospatial analysis that are funded by the Office of Naval Research (ONR) and DARPA, that the MURI team may exploit and leverage. NAWCWD can profit significantly by interacting with the DeVore led team and Drs. Gary A. Hewer and Alan Van Nevel. Their Navy colleagues can help assure that the MURI research is as relevant as possible to the Naval Air Systems Command mission.

3. Future Naval Capability (FNC) efforts proposed by NAWCWD for FY09 emphasize automated image understanding for tactical environments. Any mature research arising from the MURI would be of great interest to Drs. Hewer and Van Nevel's FNC team, and every effort will be made to transition new technology to Navy users.

ALAN VAN NEVEL

Copy To:
Prof. Ron DeVore, University of South Carolina
Prof. Stan Osher, University of California, Los Angeles

AMSRD-STTC

November 13, 2006

Dr. Andrew J. Kurdila
Virginia Polytechnic Institute and State University
305 Durham Hall
Blacksburg, VA, 24061

Dr. Kurdila:

This letter is to express the US Army's Research Development and Engineering Command (RDECOM) Simulation and Training Technology Center (STTC) support and interest for your MURI proposal entitled *Model Classes, Approximation, and Metrics for Dynamic Processing of Urban Terrain Data.*

Recognizing the need for better research in the area of terrain processing, RDECOM-STTC has invested time, energy and dollars in several attempts to develop solutions to some of these issues. However, in order to really provide accurate solutions to these complex problems and take this to the next level, we agree that it is going to take a collaborative effort from world class researchers in mathematics, engineering, and computer science to address the full spectrum of terrain modeling problems. Consequently, the universities that you've pulled together The University of South Carolina, Rice University, Princeton University, UCLA, Texas A&M University, University of Texas at Austin, and UC Irvine, appear to be the perfect assembly of scientists that can provide the proper research to ultimately generate the solutions to this serious deficiency.

After reading your proposal/plan to provide comprehensive development of both theory and algorithms, RDECOM-STTC endorses your MURI proposal and recognizes it as extremely important, valuable and applicable to the insufficient and inaccurate terrain data problems. Hopefully, your collaboration with JOUSTER and all of its capabilities ensure the ultimate success of this research venture.

We thank you and your colleagues for this initiative and look forward to the DOD and civilian sectors benefiting from its success.

Sincerely,

Dr. Neal M. Finkelstein
Deputy Director (A), Simulation and Training
Technology Center

Mr. Irwin L. Hudson
RDECOM-STTC, JOUSTER – PD