Efficient representation of 3D human head models

Sarp Ertürk[1] and Tim J. Dennis[2]
[1]Department of Electronics and Telecommunications Engineering
University of Kocaeli
Izmit 41040, Turkey
[2]Department of Electronic Systems Engineering
University of Essex
Colchester CO4 3SQ, UK
s_erturk@hotmail.com, tim@essex.ac.uk

Abstract

Human head models are used in many applications of computer graphics such as computer animation and cyberspace communications. Spherical harmonic shape representation decomposes the surface into its spatial surface frequency components by 3D multiresolution techniques. This paper demonstrates that spherical harmonic representation is particularly suited for modelling of the general 3D human head shape due to the originally rounded surface geometry. Operating from range data the SH representation ignores fine surface detail and retains the general shape suitable for texture mapping. The SH surface is represented with a limited number of bases function coefficients, analogous to Fourier series decomposition. It is shown that the total data amount to represent any human head SH model can be limited to a few thousand *bit*s, with quantized and variable-length coded parameters. The SH models can be reconstructed from the parameters in wire-frame format at the desired polygon resolution and post-processed with conventional graphics utilities.

1 Introduction

Three-dimensional object shape representation is used in computer graphics, computer aided design, animation, object visualisation, object-oriented video coding and object recognition applications. Spherical harmonic (SH) shape representation is one of the techniques available for this task [1]. Spherical harmonics are derived from Laplace's equation being solved in the spherical coordinate system, and form a complete set of eigenfunctions orthogonal in continuous space [2]. The completeness and orthonormality properties of spherical

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harmonics enable any arbitrary 3D real function to be expanded in a series of weighted SH bases, as long as the surface can be defined in spherical coordinates by single-valued radial (range) distances.

Spherical harmonics form a set of ordered spatial surface frequency (SSF) functions defined on the unit sphere in terms of the angular coordinates. The SH representation decomposes the object into its spherical SSF components. Dropping high order harmonics a compact representation of the general object shape is retained ignoring fine surface detail.

The spherical harmonic surface representation is given in the form

$$R(\theta,\phi)=\sum_{l=0}^{L}\sum_{m=0}^{l} A_{lm}U_{lm}(\theta,\phi)+B_{lm}V_{lm}(\theta,\phi)$$

with

$$U_{lm}(\theta,\phi)=\cos(m\theta)\sin^{m}(\phi)P(l,m,\cos\phi)$$

$$V_{lm}(\theta,\phi)=\sin(m\theta)\sin^{m}(\phi)P(l,m,\cos\phi)$$

The spherical coordinate system is defined by the coordinate notation (R,θ,ϕ). U_{lm} and V_{lm} are the SH basis functions defined in terms of the associated Legendre polynomial $P(l,m,x)$. A specific shape is constructed by adjusting the SH parameters A and B for each basis function accordingly. L is referred to as the representation order and sets an upper limit to the series expansion. The representation order governs the smoothness and detail of the SH model, by controlling the highest SSF included. The degree of the spherical harmonics is represented by l, while m is used to differentiate between harmonics of the same degree.

Sample basis functions of U_{lm} up to the third degree are displayed in magnitude form in Figure 1. The basis functions V_{lm} are zero for m=0 and rotated versions of U_{lm} otherwise. As the SH bases can take negative as well as positive values, in the figure darker colours are used for positive valued surfaces whereas lighter colours for negative values. The zero-order harmonic is constant valued and represents a sphere in 3D space, analogous to Fourier series it is referred to as the DC harmonic.

Spherical harmonic shape representation has been used for molecular surface visualisation [3], object recognition [4], object orientation calculations [5], visualisation of human internal organs [6] and reconstruction of shape deformation [7].

3D human head models are commonly used in computer graphics applications, mainly in the animation of humans for image sequences [8] and model-based video coding [9]. Furthermore injury analysis in medical applications [10] as well as design and analysis of professional headgear, such as helmet design for military use [11] make use of human head models.

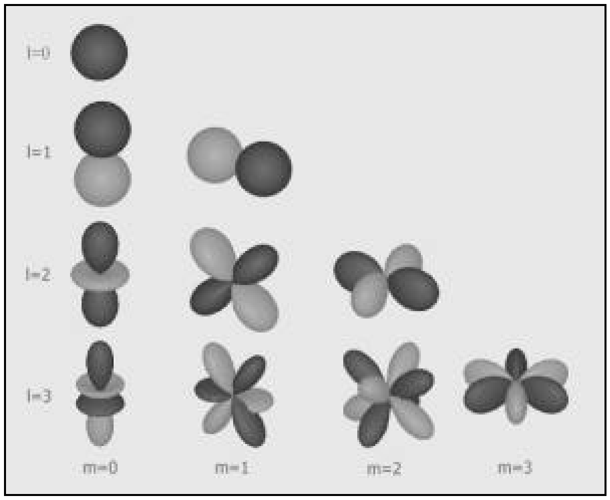

Figure 1: SH basis functions U_{lm} up to the third degree.

This paper presents the employment of spherical harmonic shape representation for 3D human head models. The main focus is on the efficiency aspect of the representation, while SH analysis and synthesis is covered essentially. It is shown that compared to 3D range data, SH models represent the general head shape ignoring possible fine detail. Because of the rounded head geometry the head shape can be acquired with a limited set of SH parameters. While the general head shape is sufficient for some applications, such as headgear design, compensation for fine detail loss can be achieved by texture mapping for others.

2 Spherical harmonic analysis-synthesis

Object shape can be acquired in the form of 3D range data sampled over the object surface using 3D scanners, computed tomography (CT), magnetic resonance (MR), stereoscopic vision systems, or from monocular view image sequences using 'shape from contour', 'shape from motion' or 'shape from shading' techniques. Although spherical harmonics are analogous to Fourier series, one major difference is that SH functions are not orthogonal in discrete space. Therefore an analysis procedure in the form of the fast Fourier transform (FFT) is not applicable to spherical harmonics. A similar sequential analysis technique has been proposed in [12]. The SH parameters are computed from the following equations, while residual error update and computational iteration accomplish compensation for discrete space non-orthogonality.

$$A_{lm} = \frac{\sum_{\text{all}\theta,\phi} r' U_{lm}(\theta,\phi)}{\sum_{\text{all}\theta,\phi} U_{lm}^2(\theta,\phi)}$$

$$B_{lm} = \frac{\sum_{\text{all}\theta,\phi} r' V_{lm}(\theta,\phi)}{\sum_{\text{all}\theta,\phi} V_{lm}^2(\theta,\phi)}$$

The computation is performed sequentially starting from the DC parameter up to the last parameter of the representation order L. After each parameter is computed, the corresponding SH radial contribution is subtracted from the current residual error values, noted as r', to leave the radial amount that still needs compensation. After an initial estimate is obtained for all parameters, 'fine tuning' is achieved by additional iterations using the residual error values remaining at the end of the former stage and progressively adding computed values to the corresponding parameter estimates.

Spherical harmonic synthesis aims to reconstruct the SH model in polygonal format for compatibility with conventional systems. The surface geometry is simply obtained by computing radial values for chosen angular coordinate pairs from the computed SH parameters. The angular sample coordinates have to be chosen so that polygonal connectivity can be established, preferable with uniform resolution. While uniform sampling in spherical coordinates is limited to twelve sample-points [13], the geodesic polyhedra of Buckminster-Fuller can be employed to achieve a nearly uniform sample pattern over the unit sphere [14]. The resultant pattern is suitable for objects with rounded geometry, such as a 3D human head, but can be improved for arbitrary object reconstruction by constructing the sample pattern on the SH surface itself instead of the unit sphere, and providing adaptive subdivision of triangles according to facet size.

3 Spherical harmonic human head modelling

As spherical harmonics are functions defined on the unit sphere, the human head is a particularly suitable object for SH modelling because of it rounded geometry. Furthermore the surface is single-valued in the radial coordinate once the coordinate system centre is located within the object, typically by translation of the coordinate system origin to the centre of gravity (CoG) of the object.

The human head SH models can be reconstructed on pre-defined geodesic sample patterns, so that corresponding spherical harmonic basis function values are available beforehand and the model geometry can be constructed by simple multiplication of parameters with pre-stored function values, in very little time. The connectivity mesh of the geodesic structure is used directly for the polygonal pattern of the reconstructed SH model.

Figures 2-4 show human heads reconstructed from scanned polygonal models as well as the corresponding SH models of order 25. While the representation order can be determined according to the desired model accuracy or the resultant data amount [15], experimentally it has been found that orders of 15-25 are sufficient to obtain appropriate human head models. Note that with increased order the representation of fine surface detail is improved, but at cost of increase in the number of SH parameters, thus the resultant data amount. It has been shown that SH model accuracy improves inversely proportional to the representation order, while the amount of SH parameters increases by the order square [16].

The SH head models preserve the general head shape including nose, ears and eyeholes, while fine surface detail in the eye, mouth, and hair regions is lost. The reconstructed SH models have the advantage of providing smooth and continuous surfaces, filtering discontinuities or irregular local shape deformations encountered in the scanned data. Furthermore the resolution of the reconstructed models can be adjusted by the number of geodesic samples taken on the SH surface. It has been found that about 2500 samples are sufficient to represent general head shapes, while higher representation orders will require a denser sampling pattern to ensure that detail is well represented in the reconstructed polygonal model. The SH models shown in Figures 2-4 are reconstructed with 2562 sample points, in accordance with the $2+10\times4^n$ sample points obtained by the n-times recursive subdivision of an icosahedron.

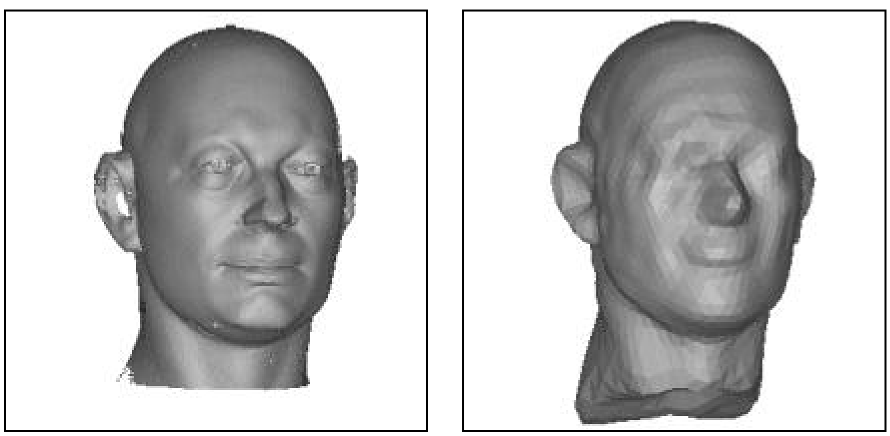

Figure 2: Head 1 and reconstructed SH model order 25

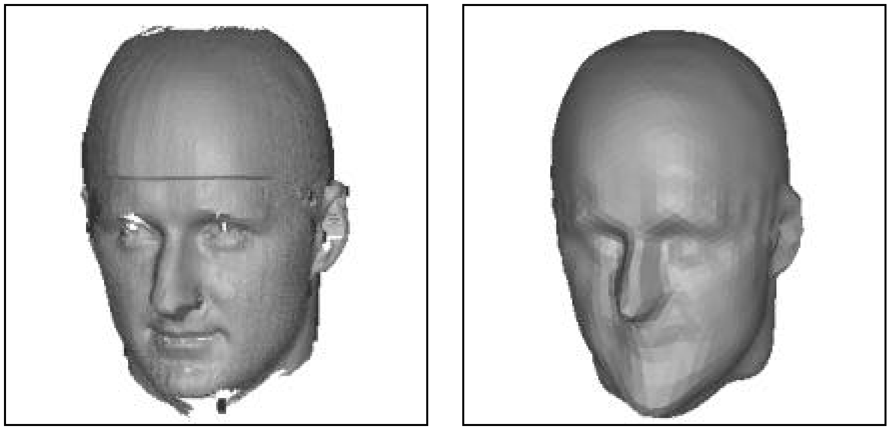

Figure 3: Head 2 and reconstructed SH model order 25

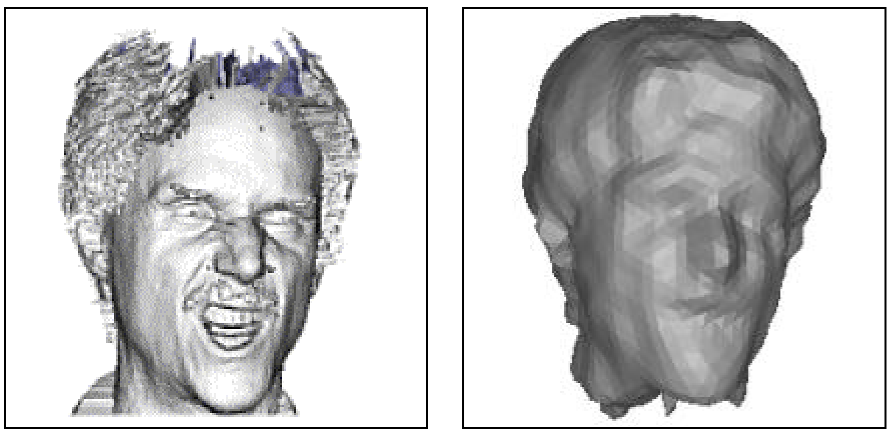

Figure 4: Head 3 and reconstructed SH model order 25

The reconstructed SH models can be texture-mapped for applications such as video coding or human animation. Figure 5 shows examples of the SH model of Figure 3, texture mapped from the front view image rotated to various orientations. Because the filtered surface detail has no significant shape contribution, the difference is not visible in texture-mapped models. Thus the texture conceals the fine detail degradations occurring during the SH modelling process. Conventional graphics tools can be used for processing, as the SH models are reconstructed in polygonal format.

Texture of the rear head is missing as only the front view image texture is used, while the texture of the back of the head shown in the images is a projection of the front facial texture. In practice texture information obtained for the entire head during the scanning process or constructed from multiple perspective view images will improve the appearance of rotated versions of the model.

It is sufficient that significant shape contributions such as nose, ears and eyeholes are well represented by the SH models to avoid texture sharing for rotated versions of the texture mapped models.

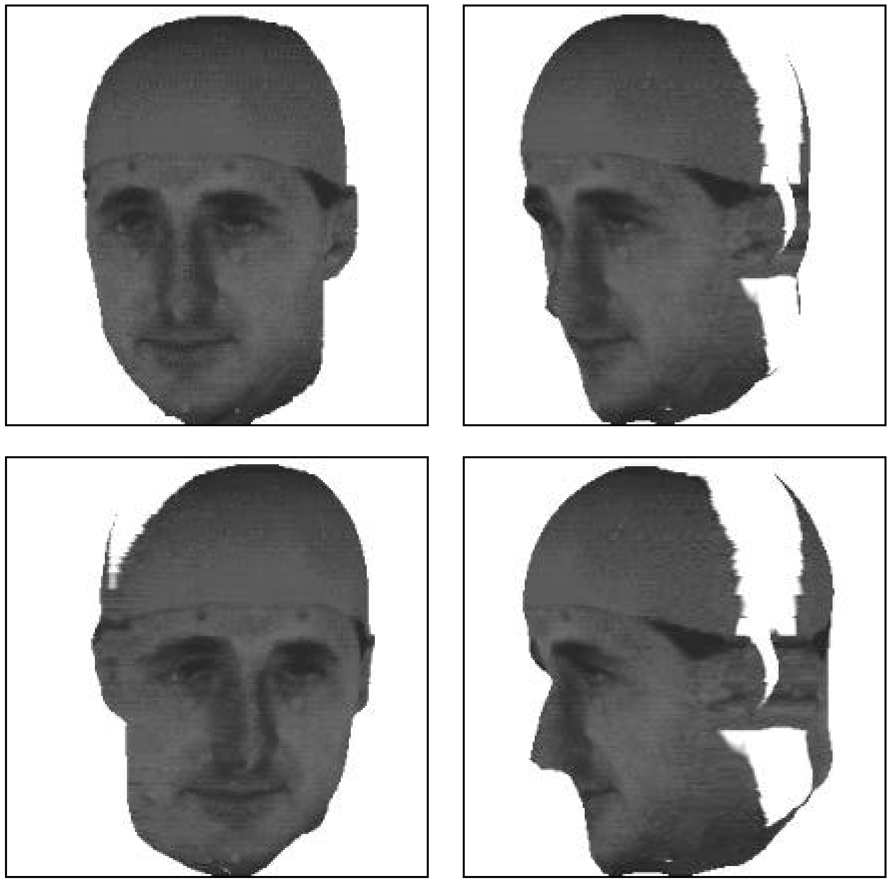

Figure 5: Texture-mapped images of the SH model of Head 2

The corresponding vertex and triangle sizes for polygonal representation of the scanned human head forms shown in Figures 2-4 are displayed in Table 1. A polygonal compression rate of 8 bits/vertex for geometry information and 2 bits/triangle for the connectivity structure has been reported in [17], resulting in compressed data amounts of 274 Kbytes, 112 Kbytes and 435 Kbytes respectively for the three original polygonal human head models shown.

For the SH models it is known that for a representation order *L*, the number of parameters is $(L+1)^2$. The human head SH models shown are therefore represented with 676 parameters. Even if double precision floating point accuracy of 64 bits/number is used, the total SH data amounts sum to 5.3 Kbytes. Hence the SH models provide an efficient representation with high compression ratios compared to the original range data.

Object	No. of vertices	No. of triangles
Head 1	187 166	373 813
Head 2	76 756	151 674
Head 3	297 820	591 495

Table 1: Size of polygonal range data

In brief, spherical harmonic representation provides a low SSF model of the human head, dropping fine surface detail but acquiring general shape features appropriate for applications requiring the gross head shape or those involving texture mapping. As the SH representation is defined by a limited set of SH parameters, an efficient definition of human head shapes is achieved. The following section demonstrates compression of SH parameter data with quantization and variable length coding.

4 Quantization and coding of SH parameters

Figures 6, 7 and 8 show the SH parameter distributions (histograms) for the given heads. For each model, the parameter amplitudes are quantized with a step size of 0.1, and the vertical axes show the total number of occurrences for each amplitude level. Typical to frequency decomposition, the DC parameter has the largest amplitude of about three times the average surface radius, and is excluded in the Figures. The DC parameter has comparatively larger amplitude than all other parameters; therefore using a separate quantizer-coder reduces the required range for the rest of the parameters, enabling higher compression rates.

Because of the high concentration of SH parameters in low-amplitude regions, very small step sizes at the low amplitudes would be needed for histogram equalisation with the non-uniform quantizer. Because of the low quantization error introduced anyhow, it is possible to allow larger step sizes so as to increase the number of occurrences of each level, achieving better data compression using variable length coding (VLC).

The SH parameters are clearly concentrated in the low-amplitude regions of the histogram, with the majority falling into the range (-1,1). Furthermore the distributions are fairly symmetric about the zero amplitude level. An optimum Lloyd-Max quantizer in the sense of minimal squared quantization error (MSQE) can be constructed for any specific SH model as it is represented by a discrete set of numbers [18][19]. However the quantizer parameters will result in comparative data overhead. Furthermore the relation between quantizer distortion and resulting shape distortion is nonlinear as SH basis functions have variable influence on the calculated model radius. Thus a Lloyd-Max quantizer in MSQE sense is not guaranteed to ensure minimum shape distortion.

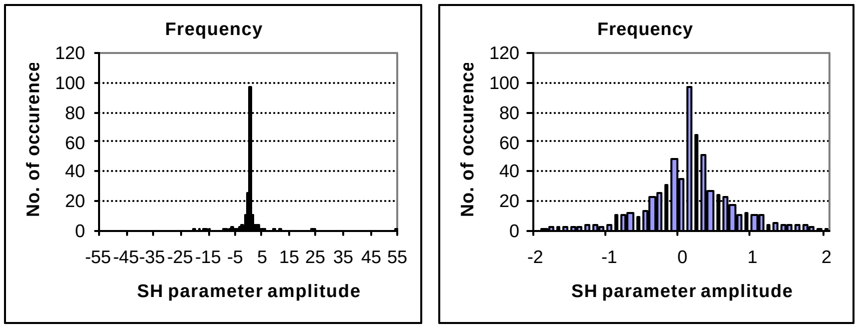

Figure 6: Full and low-amplitude range SH parameter histograms for Head 1.

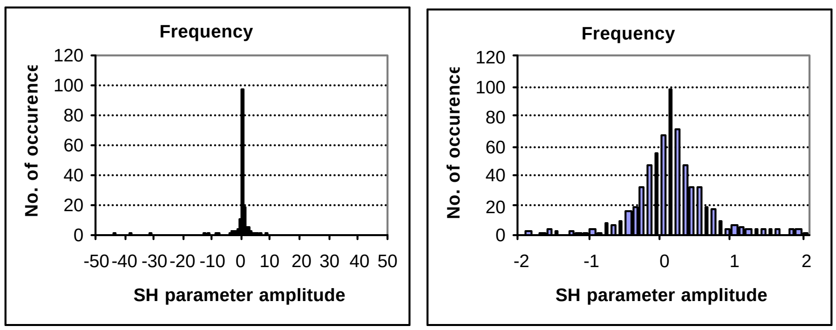

Figure 7: Full and low-amplitude range SH parameter histograms for Head 2.

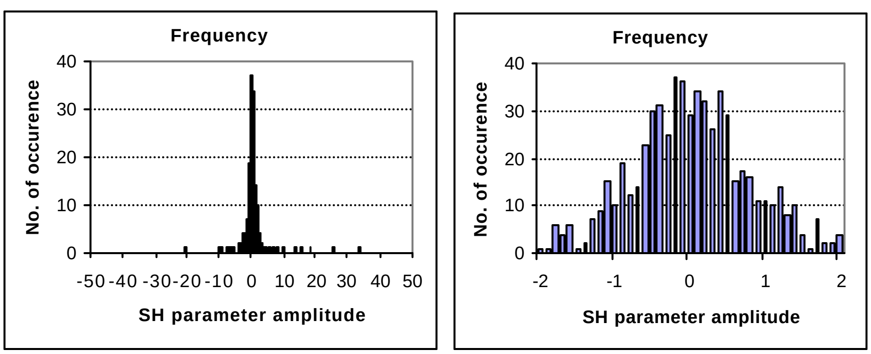

Figure 8: Full and low-amplitude range SH parameter histograms for Head 3

As the parameter histogram is reasonably concentrated in low-amplitude regions, a close performance to Lloyd-Max can be achieved with simple non-uniform quantizer schemes. Typically the low amplitude input range is assigned smaller step sizes to reduce the resultant distortion. Assigning shorter codewords for low amplitude levels with higher frequency ensures efficient compression by VLC.

A sample quantizer-coder constructed by manual selection of parameters is given in Table 2. Huffman codes [20] are used to switch between the different parts of the quantizer and additional fixed length codes are used to select the corresponding representation level, in a similar approach to the JPEG coding algorithm [21].

Parameter Range	Step size	No. of levels	Codewords
[-0.7,0.7]	0.1	15	'0'+ 4 bits
[-2.2,-0.8][0.8,2.2]	0.2	16	'10' + 4 bits
[-64,-2.5][2.5,64]	0.5	<256	'11' + 8 bits

Table 2: Example quantizer-coder scheme

With the example quantizer the SH models for Head 1, Head 2 and Head 3 are represented respectively by a total of 3 730, 3 624 and 3 882 *bit*s (one *bit* corresponding to a single computer digit) only. Thus on average about 5.5 bits per SH parameter is required. The resultant modelling error compared to the range data is in average about 0.8 voxels for the SH models, in terms of the average absolute radial error, less than 1% of the average surface radius. In either case the modelling error caused by quantization is less than 0.1 voxels. The variable length coding process itself is a lossless compression scheme. Compared to the several megabits required to represent the models in range data polygonal form, a large compression ratio is achieved.

4 Conclusion

It has been shown that spherical harmonic representation provides an efficient way to represent 3D head shapes. The SH model drops fine surface detail and preserves general shape features. It is possible to compensate for the detail loss completely by texture mapping. Furthermore it has been presented that SH parameters are highly concentrated in the low-amplitude regions of the histogram. Using quantization and variable-length coding SH head models can be defined by a data amount of a few thousand *bit*s only.

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