

3D画像処理に基づく人体組織の形状解析 —研究の糸口へのノート

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要旨 CT装置などで取得される人体の3次元デジタル画像(3D画像)を入力として、臓器、組織の形状を解析するために現在用いられている手法、あるいは利用可能と思われる方法の基礎を簡単に紹介する。対象の3D画像は濃淡値を伴う、いわゆる濃淡画像であるため、人の目は内部まで見通せない。そこで可視化の手法が必須となるため、可視化手法についてもふれる。実例として、実際の人体胸部、腹部の画像とそこに現れる形態の例を示す。

1 人体組織の形状解析の問題点

1.1 セグメンテーションの必要性和形態の知覚

- ・対象物を切り出して、始めて物体の形状を人は知覚できる。物体 \leftrightarrow 背景を区別する
→切り出し操作(=セグメンテーション(segmentation))が必要。

これを人が行うか 自動化するか。

人が行う ○人の理解を反映。○慣れれば安定 ○自動化手法不要
×手数がかかる。 ×客観性に欠ける。

自動化する ○手間を要しない ○客観性を増す ○定量化向き
×セグメンテーション法が要る ×正確に行うのは易しくない。

セグメンテーションはCADでは最もよく研究されているテーマの一つである。例えば、[科研06, 特集04] 参照。

- ・切り出されていなくても、形態は認められる
→例えば、等濃度面、ボリュームレンダリング画像。

後者は、現在、医用画像では常用されている。バーチャルエンドスコープ、など。○セグメンテーション不要 ×計測はできない。×パラメータ依存性。

1.2 形状情報の種類

- ・単一の孤立物体：幾何学的特徴量。いわゆる“形”と“大きさ”
- ・複数物体の位置関係、配置の特徴(ボロノイ図など)
- ・多数の物体の分布状態：パターン認識で言うテクスチャ特徴
- ・トリー、グラフ、ネット：分岐、交差、階層
- ・トポロジー特徴：穴、空洞、連結性、結び、絡み、オイラー数

1. 3 濃淡値の空間分布に認められる形状特徴

- ・尾根、谷、鞍部 3次元空間では4次元曲面の形状特徴
- ・等濃度面の形状

1. 4 観察のスケール — 空間解像度

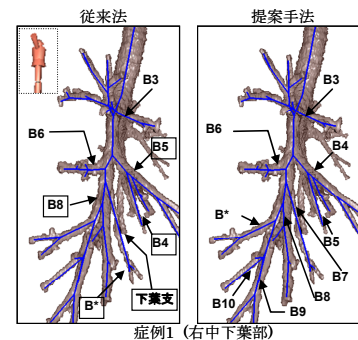
- ・ナノスケール（遺伝子 原子・分子）—マイクロ（細胞、微細組織）—ミリ（臓器）—メートル（等身大）
- ・電子顕微鏡—光学顕微鏡—マイクロCT—CT—モーショキャプチャ
- ・インタラクティブにスケール可変の可視化 広義のナビゲーション [モリソン83, 鳥脇04]

1. 5 人体組織の形状の特色

- ・数理的表現の難しさ、不適合性—マクロには合うが、臨床に意義のある箇所です実用に十分な精度では合いにくい。肺がん病巣は実寸2～3mmのものを見つけない。その形状変化量はさらに小さい。
- ・複雑な形状が空間的に広がる。例えば、胃や大腸の内壁面、血管系、など。
- ・軟組織の変形や形状を扱いたい、現状では難しいものが多い。
- ・自然な状態での計測が難しい。

1. 6 形状情報の意義、用途

- ・モデルの導出 血管、気管支の分岐 [例えば、江間05、Mori00]
- ・セグメンテーションの基礎情報 [例えば、目加田05]
- ・判断、決定の基礎情報 [例えば、目加田05]
- ・分類と名称決定 [例えば、江間05]



1. 7 2次元から3次元へ次元に関する拡張性

2次元画像の場合は、人は極めて容易に全体を知覚し、理解できる。しかし、3次元の場合、とりわけ3次元濃淡画像の場合は直接に全体を知覚できないため、人の理解には大きな制約が加わる。計算機による画像処理の手法は、2次元画像用の手法が3次元画像に直ちに拡張できるとは限らない。2次元から3次元への拡張性の観点から、主な手法の性質をまとめたものを [鳥脇02] から引用する。

(1) 次元数に無関係なもの

点演算：しきい値処理（しきい値選択，2値化，n値化，正值（負値）クリップ），階調処理（ガンマ補正、圧縮、伸張，等）

濃度値の統計的処理：ヒストグラム操作（均等化、圧縮、伸張等）、局所統計量計算

画像定数間演算，画像間演算：四則演算・比較（画像定数間，画像間），量子化

(2) 理論的にも実行形式も直接拡張可能なもの

直交変換：フーリエ，アダマール・ウォルシュ，余弦，等。

対応する離散変換（DFT、など）も含む。

周波数領域処理：特定周波数の除去，抑制，強調

幾何学的変換：アフィン変換，2次変換，等

幾何学的特徴抽出：モーメント，面積，体積，等

局所処理：局所統計量フィルタ（最大値フィルタ，最小値フィルタ，など）、

モルフォロジーフィルタの一部，

領域生成：分割併合，領域成長（各種尺度による）

連結成分処理：図形融合

(3) アルゴリズムの具体化には工夫を要するが、原理的には同一の考え方でできるもの

局所処理（フィルタ）：平滑化，モルフォロジカルフィルタ，差分型（グラディエント，ラプラシアン，各種局所差分，レンジ，一般線形フィルタ，非線形フィルタ，モルフォロジーフィルタ

強調・平滑化：ヒストグラム変換，線形フィルタ，ノイズ除去フィルタ，

中央値フィルタ，エッジ保存平滑化，最大値フィルタ，最小値フィルタ，

モルフォロジーフィルタの一部，ガウス型，空間微分（差分）

復元：ウィーナフィルタ，最小二乗誤差復元

連結成分処理：ラベル付け，距離変換

領域生成（特に3次元固有の性質を使う場合）。

ボロノイ図の計算

線図形処理：接続，枝除去，平滑化，チェイン符号化，距離変換

スケールスペース

(4) 3次元独自の性質から直接拡張は困難なもの（理論的な性質，または，アルゴリズムの大幅な複雑化による）

図形のトポロジー：消去可能性判定，オイラー数計算

連結成分処理：図形収縮，細線化，薄面化，境界追跡、結び・絡み処理

その他任意の近傍演算：場合の数が膨大なもの。例えば，エッジ保存平滑化

図形形状特徴抽出：フーリエ記述子，穴（ハンドル）の個数と大きさ

特徴抽出：フーリエ記述子，隣接関係グラフ，ボロノイ図の形状

2 人体組織の形状の具体例

付録に筆者の一論文を添付する。これはFORMA（形の科学会英文論文誌）から許可を得て転載するものである。ただし、テキスト部のみで、画像はすべて略す。本雑誌は電子ジャーナルであり、<http://www.scipress.org/journals/forma/list.html>より参照できる。

3 仮想化された人体

近年、人体の特性を3次元デジタル画像（あるいは形状記述）としてモデル化し、様々

の利用に供しようとする試みが多数見られるようになった。主な例を以下に示す〔鳥脇06〕。

•Visible human (米)

公開の画像データベース 特定人体2例のボクセルデータ。用法としては汎用モデル

・Voxel Man (独 ヘーネら)

Visible human の高度CGによるリアルな可視化。ボクセルモデルに構造化情報を入れる。主に解剖学テキスト

・Sensible human (日 高橋ら 人体組織の特性値) [高橋00]

・in silicon Human (日 赤沢ら 細胞、組織、器官 シミュレーション) [特集05]

・ソフトクローン (米 浅田 生理データ 健康管理用モデル) [日経05]

・電体新書 (日 科研費特定研 人体データベース) [科研06]

・デジタルヒューマン (日 人体モデル) [特集05]

4 むすび

本小文では、形状情報に関する研究の糸口となりそうな項目に関する筆者の現在の考えと関連する資料を記した。形状情報や“形”に関する研究は本質的に学際的である。それだけに明確に体系化されているとは言い難い。その広がり的一端を知るには、筆者も一部関係した〔形04, 高木03〕、および、形の科学会の会誌および論文誌FORMAを是非参照されたい。また、3次元デジタル画像処理に関しては〔鳥脇02〕に有る程度まとめられている。

しかし、一方ではあらゆる分野において“形”は人手によって解析され、計測されてきている。従って各分野において、どのような“形”に注目するか、何を計測するか、に関して各分野毎に固有の知識が蓄積されてきているとも言える〔例えば、Lusted77〕。その中で近年の大きな展開として、“形”の計測や認識にもコンピュータが利用できるようになったこと、および、CTなどによって物体の内部も含めて3次元的計測が非破壊でできるようになったこと、がある。その意味では、“形”の研究も新しい時代に入っていると考え、今後の発展を大いに期待している。

なお、本文作成は準備時間が極めて制約された中での作業であったため、内容も参照資料も非常に限られた範囲に止まる事をお断りしておきたい。

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付録 以下の論文は、FORMA（形の科学会英文論文誌）に採録決定しているものを許可を得て転載するものである。同誌は電子ジャーナルで、本文はVol.2005 2 0 0 6 年 3 月掲載予定。ただし、図版は略。原文は<http://www.scipress.org/journals/forma/list.htm> から参照できる)

Review paper

Visualization of Forms in the Inside of the Human Body

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Abstract This article presents a brief review of methods to visualize forms of parts of the human body in different spatial resolutions by applying navigation observation and pattern recognition to three dimensional (3D) X-ray CT images. Several examples of 3D views of the parts of human body are shown. They are characterized by that the viewpoint is selected arbitrarily inside the body and moved around anywhere almost continuously.

1 Introduction

Human organs have very complicated form, sometimes far beyond our imagination. We need to know forms of various parts of organs and tissues as exactly as possible to diagnose diseases and treat them because some kinds of changes will be observed necessarily due to diseases. Apart from such medical requirements forms of human body or parts of it will be helpful to creative activity such as painting and sculpture, animation production, and industrial design

Recent development of technology has made it possible to see forms of various parts of human body without injuring it. In particular, imaging technologies such as CT and MRI in medicine contribute much (DUCHMAN 2000). For instance, by 3D X-ray CT we can reconstruct parts of human body on computer memory with 0.5 mm³ of spatial resolution. Molecular imaging provides a method to record functions and shapes of molecule level. By micro CT we can observe microstructure in the spatial resolution of micron-meter order (MATSUBARA 2004, SATO2004).

In this article, the author presents a brief review of methods to visually observe or to visualize forms of parts of human body in different spatial resolutions by applying navigatio

n observation and pattern recognition to three-dimensional (3D) X-ray CT images. We also show several examples of 3D views of the parts of human body. They are characterized by that the viewpoint is selected arbitrarily inside the body and moved around anywhere almost continuously.

By imaging technology, we obtain a 3-dimensional array recording the parts of the individual human body. This is regarded as a virtualized version of the individual human body.

We call this the virtualized human body (VHB) (TORIWAKI 1997). VHB is a replica of the individual human body. However, we (human visual system) cannot see such a set of 3D numerical values directly. In order to visualize it we employ a CG technique known as the volume rendering (LEVOY 1988, TORIWAKI 2002). Visualization methods are more enriched by combining them with navigation and structurization.

2. Visualization of 3D images

In the case of the observation of the human body, the original data is a set of three dimensional (3D) density values obtained by scanning human body by imaging equipments such as X-ray CT and MRI. We call this 3D array a 3D digital picture (image)(Toriwaki2002c). The 3D array of numerical data stores physical measurement data of 3D volume elements of the human body such as the attenuation factor of X-ray measured by scanners. The spatial resolution spreads over the range of 1 cm to 10 μ m. However we cannot see directly the inside structure of such 3D array of numerical data unless utilizing visualization techniques.

The visualization technique that is employed most widely now is the volume rendering (VolR). We do not intend to explain details of VolR here. Details will be found in (TORIWAKI 2002c, MORI 2003), if necessary. Instead we will give brief comments to be noted in seeing images rendered with VolR below.

(1) VolR is considered as a kind of the orthogonal or the perspective mapping of a 3D array of numerical data (or a solid) to a 2D picture plane. Therefore a gray tone value (density value) on a resulting 2D picture is an accumulative sum or multiplication of density values of an original 3D picture along a line of mapping (called "the ray" in the field of computer graphics)(MORI 2003) (Fig.1).

(2) Before generating a VolR picture, we replace density values by suitable values, usually for the convenience of understanding spatial distribution of original density values by human vision.

The resultant values of replacement are called "opacity". Correspondence relationship among density values and opacity values is defined by the opacity table, which is most important parameters of VolR user can select.

(3) Voxels in a 3D picture may be divided into subgroups if possible, so that different colors may be assigned to each subgroup. By using colors we can attract observers' attention to particular objects in a displayed picture. Assignment of colors is defined by a color table in the VolR system, which is the other important parameter given by a user.

(4) If a solid object in a 3D space is defined explicitly, we can draw the surface of the solid object on a 2D display. This is done by another well known method of computer graphics "surface

ce rendering (SurR)". We will neglect explanation of SurR here, because it is also found in any textbook of computer graphics easily (WATT 1998).

(5) From the viewpoint of shape understanding, VolR is considered as the method directed to discovering or finding form existing in natural phenomena or natural things without much a priori knowledge. As was introduced above, it contains two sets of parameters "opacity table" and "color table". Observed forms or resulting "impression" of generated images greatly depends on these two parameter sets.

(6) On the other hands, SurR is the method directed more strongly toward design or creation of a new form artificially. In order to apply SurR to natural objects such as the human body, we need to extract border surfaces of objects beforehand. To perform this automatically, pattern recognition of solid objects or border surfaces in 3D space is required (TORIWAKI 2002c). Details of pattern recognition are omitted here because important parts of it have already been described in (Toriwaki2002)

3 Navigation

In the ordinary volume rendering, we assume a fixed viewpoint and fixed view directions. Also we set necessary parameters fixed such as opacity parameters. Although all of them may be given arbitrarily, they are fixed once they were given. In several applications, however, parts of viewing parameters (positions of viewpoints and view directions) may be changed interactively by users. In medical applications this technique is well known as virtual endoscopy nowadays (ROGALLA 2000, VINING 1993, 2003, MORI 1994). Sometimes they are called by the name of the target organs to be diagnosed such as virtual colonoscopy and virtual bronchoscopy (ROGALLA 2000, DUCHMAN 2003).

Technically this is not difficult if recent computers with graphic engine are available. Let us represent a two dimensional (2D) picture sequence by $F = \{ F(t) \} = \{ \{ f_{ij}(t) \} \}$, where $f_{ij}(t)$ means a gray tone value at the i -th row and the j -th column at the time t . If we generate a 2D image $F(t)$ in the suitable rate, faster than 10 frames/sec, for example, with changing the location of the view point gradually we can produce a moving picture sequence which gives the impression that we fly through the inside of tubular organs such as colon. We call this way of presentation the navigation (TORIWAKI 1997). The picture sequence F is a time sequence of 2D pictures $F(t)$, which shows a scene, seen when our viewpoint moves along the time axis. This is not the only possible way of the viewpoint movement. Conceptually various types of navigation along other axis will be considered. We call this the generalized navigation or navigation observation (TORIWAKI 1997,2004a,b). One interesting example is the change in the physical scale, or the magnification. The example is found in (MORROSON 1982).

In general, by seeing generated picture sequences we can get feeling that we are traveling inside the object or inside abstract space along a suitably defined axis. In this sense, virtual endoscope images show moving images which might be seen during driving cars or airplanes inside human body or flying through pipeline shape of organs along their inside wall with small airplanes. These feelings are aroused from the moving of a viewpoint also

ng the real world coordinate axis. Conceptually the movement of the viewpoint along various others axis are considered, such as the physical scale, opacity, and time (Toriwaki2004a).

4. Collective examples of inside views of the human body

Let us show examples of pictures generated by rendering applying VolR and SurR to 3D CT images of real human body. They have been produced and collected in the process of researches in authors' group concerning computer aided diagnosis of cancer, pattern recognition of 3D images, computer graphics, and visualization of 3D gray tone pictures. We do not intend here to give accurate medical meanings to those images. Instead we expect readers to enjoy views inside human body. Also they could find how complicated forms exist inside our body that is usually invisible.

4.1. Example 1: The inside view of colon

The first picture is the view of the colon (ODA 2004, HAYASHI 2003a,b, KITASAKA 2004). Fig 2 shows the outside view of colon. Blue curves show approximated center lines automatically determined by a 3D thinning algorithm (SAITO 1994, 1995, TORIWAKI 2001). If observer's viewpoint proceeds into the colon along these centerlines, the observer can see scenes of the space inside colon. Let us show in Fig 3 an example of a picture sequence, which is consisting of successive scenes obtained by virtual colonoscopy. The colon wall has many successive convex and concave parts called "haustra" in medicine. By presenting each scene with the enough high rates, we can feel as if we are flying through the cylindrical closed space. In clinical applications doctors are expected to find symptoms of diseases such as polyps, tumors and inflammations.

Fig 4 illustrates effects of changes in the opacity table using one of such scenes of the colon wall. Here a typical polyp exists, but its apparent shape seriously varies according to the values of the opacity table of the VolR algorithm employed here. Thus we should be careful enough concerning what we are seeing in VolR images.

4.2. Example 2: The inside view of the lung

Let us proceed to the scenery of the lung. Fig 5 presents two scenes observed from the viewpoint located inside the lung. Parts of blood vessels, bronchus branches, ribs and chest wall are seen in the picture. Small massive objects in the right picture, which seem to be floating in the air, are nodules suspected to be lung cancer. In this case more than 100 such small nodules were detected by a medical doctor. We can move around them, if needed for diagnosis. Those are marked by areas of green color at the corresponding locations in the left picture. Such nodules are recognized as only small vague massive shadows scattered in the lung field of a slice of CT images. In these 3D images we can fly around among such many 3D nodules freely with examining details of shapes and calculating shape features. Even in this case, however, borders of

nodules are not fixed decisively. They are only perceived visually in VolR images. Apparent shapes of nodules are very sensitive to values of the opacity table employed here (Fig.6)(KUSANAGI 2003, MEKADA 2003).

4.3 Example 3: Microstructure of lung tissue

The third example is the visualization of microstructure of the tissue of the lung. Source data was obtained by scanning a piece of an inflated fixed lung with micro CT scanner. Its spatial resolution is $0.2 \mu\text{m}$ approximately. Let us omit here detailed explanation of medical or anatomical contents of the structure. We would like to notice that the sample was made after a piece of an anatomical sample was dried. Therefore the structure seen here is a kind of skeleton structure of the architecture in living organ. However the approximated shape was preserved because the sample was filled with air after it was extracted and then dried (GROSKIN1993). The whole of the piece of the sample is shown in Fig.7. Fig8 shows an example of a slice of the CT image, and Fig9 is a VolR image of the whole of the sample. The real size is about 5mm^3 .

Let us show in Fig.10 a VolR image with the viewpoint inside the piece of the sample used here. We can see the sophisticated architecture of parenchyma of the human lung, peripheral structure of thin bronchial branches, alveolar duct, alveolus etc. Basic units forming the lung architecture are the alveolus and the alveolar ducts. The number of alveolus is a key determinant of the lung architecture, and has been counted in various ways (OCHS 2004). In this sample, however, individual alveolus is expected to be observed directly, because the mean size of a single alveolus was about $4.2 \times 10^6 \mu\text{m}^3$ (OCHS 2004). The total number of alveoli was estimated as 480 million according to (OCHS 2004). This value was derived by applying classical stereology to 2D sections observed by light microscope. Apart from medical or anatomical meanings, we can see complicated 3D network architecture. By shifting the viewpoint a little we see different views of this architecture. In the case of Fig.10, the viewpoint is considered to be located inside a peripheral bronchus branch (left), and in the peripheral vein (right).

Shape features characterizing this architecture have not been proposed, nor been measured. In (OCHS 2004), the Euler number of this architecture was estimated only by stereological method. In (MAUTUBARA 2003, 2004), the method proposed in (TORIWAKI 2002a, b) was applied to calculate 3D digital Euler number and the connectivity index from a 3D binary picture obtained by the threshold from the 3D gray tone image. Apparently similar structure is found in bone, although the size is larger than this (KINNEY 1995, 1998, MAJUMDAR 1995, PARFITT 1983, SAHA 1996, WEHRLI 2000, 2001, 2003).

We should be careful, however, to interpret this image again, because the same problem as was described before occurs here, too. For example, Fig.11 shows two VolR images of this sample from the same viewpoint and the same direction. Only the opacity tables are different among them. <Which is true? > is the reasonable question. Perhaps, they provide information of the shapes of 3D equi-density surface at the different level of density values. Still we could have recognized some of individual alveoli by computer (SATO 2004).

4.4 Example 4 : Tree structure in the human body

Let us present several views of the tree structure in the human body. Fig.12 shows the bronchus tree and vessels extending from the hilum toward the peripheral of the lung. The gray column at the center of the image is the spine. The next image (Fig.13) is vessels in the lung extracted automatically by the image analysis procedure and then were classified into arteries and veins by the medical specialist (TANAKA 2004).

Strictly speaking, vessels and arteries in the lung are connected by capillary, but the present CT systems cannot record figures of the capillary. Thus vessels and bronchus branches are observed as the tree structures in CT images. Anatomical names are also given to individual branches regarding them as parts of tree structure.

4.5 Example 5: Abdominal organs

Finally let us show the outside views of major abdominal organs in Fig. 14. Since all organs in this figure were again extracted by pattern recognition by computer, their forms are not always exact, but important errors have not been found here (KITASAKA 2005). Anyway, we can never see such forms in living human body without X-ray CT images. However, we have not succeeded in deriving reasonable way of mathematical expressions for these forms.

5. Conclusion

In this article, the author briefly reviews methods to visualize forms of human organs and tissues as examples of forms found in natural things. By the great progress in recent imaging technologies we can obtain 3D digital images of parts of human body with the spatial resolution of $10\text{ mm} \sim 10\mu\text{ m}$. Once we have stored digitized data from scanning devices, we can reconstruct the individual human body (virtualized human body VHB) in computer. By visualizing VHB, we can see various forms existing in the human body. Furthermore we can move around or fly through inside the human body interactively.

The article presented several examples of images showing scenes inside the human body. All of them are characterized by that the viewpoint was set inside the body. However theoretical (or mathematical) analysis of those forms still remains unsolved for future problems. For instance, simple mathematical expressions for the form of colon have not been known. Shape features have not been reported for the complicated spatial architecture of the lung tissue. We expect that the science on form will contribute much to solving these problems in the near future.

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