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Curve interpolation model for visualising disjointed neural elements☆

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Abstract

Neuron cell are built from a myriad of axon and dendrite structures. It transmits electrochemical signals between the brain and the nervous system. Three-dimensional visualization of neuron structure could help to facilitate deeper understanding of neuron and its models. An accurate neuron model could aid understanding of brain's functionalities, diagnosis and knowledge of entire nervous system. Existing neuron models have been found to be defective in the aspect of realism. Whereas in the actual biological neuron, there is continuous growth as the soma extending to the axon and the dendrite; but, the current neuron visualization models present it as disjointed segments that has greatly mediated effective realism. In this research, a new reconstruction model comprising of the Bounding Cylinder, Curve Interpolation and Gouraud Shading is proposed to visualize neuron model in order to improve realism. The reconstructed model is used to design algorithms for generating neuron branching from neuron SWC data. The Bounding Cylinder and Curve Interpolation methods are used to improve the connected segments of the neuron model using a series of cascaded cylinders along the neuron's connection path. Three control points are proposed between two adjacent neuron segments. Finally, the model is rendered with Gouraud Shading for smoothening of the model surface. This produce a near-perfection model of the natural neurons with attended realism. The model is validated by a group of bioinformatics analysts' responses to a predefined survey. The result shows about 82% acceptance and satisfaction rate.

Key Words

bounding cylinder; curve interpolation; reconstruction model; Gouraud shading; neural regeneration

Research Highlights

(1) Neuron visualization with realism appearance was generated to provide accurate three-dimensional neuron reconstruction models of neuron cells. (2) The proposed framework solved the constraint encountered in the presence of virtual neuron morphology data. (3) The variations found in the study are expected to be used in future work to improve the appearance of the neuron morphology connection in this proposed algorithm.

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INTRODUCTION

Advancement and trend in computer technology has constantly challenged the scientists to seek effective tools[1] for simplifying complicated biological system of the human neurons. Neuron models and behavioural computation have been developed to assist researchers in this area for good understanding on the neurons in the human body in the last few decades. The model building is essential to produce viable theories of neuronal computation because neuronal integration involves complex interactions between large numbers of variables. Further, it is not straightforward to inspect the relationship between the neuron structure and specific function of neuronal dendrites. A number of semi-automated[2] and automated[3] systems are being developed by facilitating the investigator's requirement to make measurement, throughput, consistency and accuracy. Thus, this paper introduces a prototype for automated reconstruction of neurons derived from what is deemed essential to acquire neuron data and morphological reconstructions through modelling[4] from the same neuron.

This paper proposes neuron visualization model with adaptive realism which provides more accurate three-dimensional reconstruction model[5] of the neuron cells. This realism, built by using exact geometrical reconstruction models of neuronal morphology[6] is related to the natural biological neurons in so many ways and could become a vital tool in exploring neuronal functions. Current models provide accurate structural measurement with good identification; this has undoubtedly ease neuroscientists jobs when navigating for relationship among neuronal dendrites' morphology and behaviour; disease and its functions. However, these models and applications lack the ability to provide realism of the morphological neuronal data visualisation which could enhance system flexibility and neural network connectivity if properly done. This is a challenge for neuroinformatics and scientists to provide appropriate tools, theories and approaches in order to achieve the desired level of realism. This tool, with accurate and efficient reconstruction of neuronal morphologies, mathematical model and computational tools[7] for describing morphological complexities is therefore required for managing and communicating large amounts of neural data. Ideally, such tool should incorporate exact three-dimensionally reconstruction model in order to determine the neuron's length, diameter, surface, orientation and branching patterns[8]. Only with these measures in hand, a thorough geometric evaluation, as well as the construction of models for computational analysis can be performed.

Several methods have been developed and applied for constructing and visualizing neuron data through modelling. Basically, computer-aided reconstruction method is applied in reconstruction model for presenting neuronal morphology[9]. Reconstruction model aims to find and achieve designing minimal algorithms for generating neuron branching by reproducing the observed neuronal shapes[10] properties. Several hardware and software equipments to setup neuronal reconstruction[11] have been created in the past two decades, both commercial enterprises and in-houses lab endeavours to view a wide variety of dendrites' trees[12]. The examples of applications that generate neuron reconstruction neuron model are[13-15]. However, the significant potentials of three-dimension visualization of neuron cells remain mostly unexploited[16]. Despite the importance and significance of three-dimensional visualisations, the capacity to explore fully its application to neural data remains a challenge[17]. Realism is only achieved when a model is deeply rooted in empirical data at any given level; that is, if its parameters are well constrained by empirical data and if it correctly predicts data which has not been used to tune the model. The most outstanding neuron model developed is that of Data Driven Simulator[18]. This model, till date, is still having difficulty to perform to optimal expectations due to the limitations of human cognition and perception of neuron. Although this approach managed to provide smooth and realistic surface, it is still less suitable and has been noted for low performance due to disconnected segment that occurs in the anatomical neuron morphological visualization. This paper therefore proposes a framework to overcome the problem of disconnected neuron segments. This could help to enhance smoother neuron connectivity and the drive towards improved neuron visualisation realism.

The paper is outlined as follows: In section 2 we provide an overview of the previous works on disconnected neuron structure as a research issue. Section 3 explains how we propose to enhance flexibility of the neural network connectivity for smoother realism of the neuron visualization. In section 4, we show experimental results that justify an improvement over existing methods and techniques as well as data analysis. The paper is discussed section 5 and conclusion is provided in section 6.

PREVIOUS WORKS

The complexity of neuron morphology which is obtained from experimental data is found in anatomically precise compartmental models[14]. However, this compartmental models of neurons from these experiments, either manually or automatically with the facilitating reconstruction software could be quite tedious and time-consuming. Also the dyeing and recording reconstruction technique is only feasible for one or a few neurons at a time. Hence, a software program that is able to generate three-dimensional neuron geometries[19] and networks in compliance with experimental findings is definitely an invaluable tool. In this vein, Eberhard *et al* [14] developed NeuGen as a software for generating anatomical neurons and neural networks. This software provides an easy way to construct a single cells and complex networks as well with a large number of neurons cell. NeuGen aims to validate the stochastic model and the derived generation of neurons and neural networks[20] against available databases of manually-traced neurons in three-dimension. Researchers introduce neuroConstruct, software based on Java application developed for constructing neural network[15]. The software facilitates the creation, visualization and analysis of networks of multi-compartmental neurons in three-dimensional space after realizing that most of existing biologically realistic network models overlook three-dimensional anatomical characteristic of the brain[21]. The graphics user interface allows model generation and modification without speciality in programming. This is because no single researcher could master all the computational and biological knowledge needed for such programming. However, neuroConstruct is able to generate neuron models which can be run on a single-processor based machine. Subsequently, the range of simulations[22] that can be visualized is limited by the processor and video memory. However, it is flexible in terms of improvement to permit greater access to the internal variables of the models, easier parameter searching and model optimization are also possible. L-Neuron software studies and generates anatomical neuronal analogs with the aim to visualize virtual neurons[13]. With this software, dendrites' morphology which are usually either taken straight from experimental data or simplified with coarse approximation is neglected. But it rarely ever generates within the model in a biologically plausible way. Therefore, this limitation of neuroanatomical modelling is unexpected as dendrites' morphology is believed among neuroscientists that it contributes a significant role in neuronal integration and of recent, progress in computer graphics and three-dimensional modelling application. Currently, L-Neuron[23] is being expanded to measure fundamental parameters directly from anatomical files and to evaluate automatically which algorithm bests fits the source data. The limitation of L-Neuron is being oriented toward single-cell analysis, thus making it less suitable for studying the effect of neuronal morphology on messy and adaptive neural network connectivity.

NEURON RECONSTRUCTION MODEL FOR VISUALIZATION

This approach is proposed in order to improve the appearance of neuron morphology connection in the generated virtual neuron model[24]. It could help to provide a wrap for the neuron connective nodes in order to cover the neuron segments and produce smoother connection from first point until the endpoint of the neuron's branching. This produces a more realistic visualisation of the neuron model.

Data acquisition

This database provides neuron cell images for rat hippocampus that consists of CA1 pyramidal cell and CA3 pyramidal cells in different age as shown in Figure 1. The format of SWC for describing the structure of neuron[25] is the simplest way and has been designed to compact and use minimum amount of information and number of fields to fully describe the branching structure[26]. As shown in Figure 2, each tracing point is represented as a row of seven numbers[13, 27-28] that describes the properties of a single compartment, an arbitrarily sized piece of a segment. This digital format consists of a plain text file that each line describes the cylindrical geometry of neuronal segment and its connection to derive any morphological measurement. Generally, before the neuron can be visualized by the extractor, digitalized neuron data should be loaded into the system.

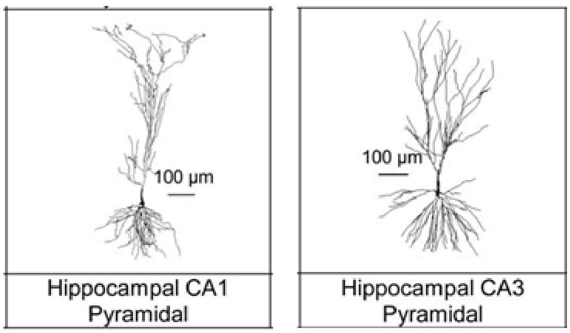

Figure 1 Sample cell of neuronal morphology used for this study[17].

ID	T	X	Y	Z	R	C
1	1	–1.5	–8.2	1.3	3.8	–1
2	3	0.8	4.2	1.4	2.3	1
3	3	21.1	41.1	1.4	1.3	2
4	3	89.2	115.1	–5.3	1.1	3
5	3	153.6	163.5	3.0	0.6	4
6	3	184.9	218.1	–2.3	0.5	5
7	3	220.9	238.7	–13.7	0.3	6
8	3	159.9	183.9	–23.6	1.1	4
9	3	211.9	270.9	–35.2	0.7	8
10	3	0.6	58.1	–2.6	1.1	2
11	3	–0.5	75.9	–18.6	1.1	10
12	3	–40.5	180.0	–55.3	1.0	11
13	3	–156.4	281.8	–65.9	0.8	12
14	3	0.3	186.8	–7.0	0.8	12
15	3	–51.5	235.7	–27.0	0.8	14
16	3	–85.2	297.6	–41.5	0.5	15
17	3	75.3	198.3	–54.6	0.8	10
18	3	130.6	228.6	–81.3	0.5	17

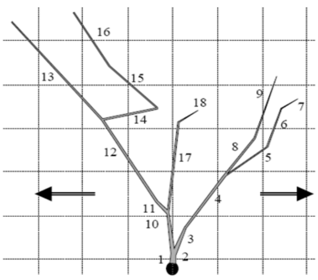

Figure 2 Digital representation of neuron morphology (right panel) from "SWC" format data (left panel)[13].

The link segment of digitalized neuron data is traced automatically from "SWC" format to produce a string of connected cylindrical compartments. The tracing process involves convertion of described neuronal morphology[29] from Cartesian data into a digital three-dimensional coordinates and branch connectivity of the corresponding trees. In this process, the link segment of digitized neuron data is traced automatically from identified format data mentioned previously. This is followed by generating branching of corresponding cylindrical neuron graphic objects to produce the morphological reconstruction. This way, neuron cells[30] are expressed with respect to the cell's anatomy in terms of a single tree representation and also in terms of the graphic cylindrical parameters.

Reconstruction and modelling

To enhance neuron nodes visualization connectivity, the integration approach of bounding cylinder[31] and curve interpolation[32] are proposed and implemented as shown in Figure 3.

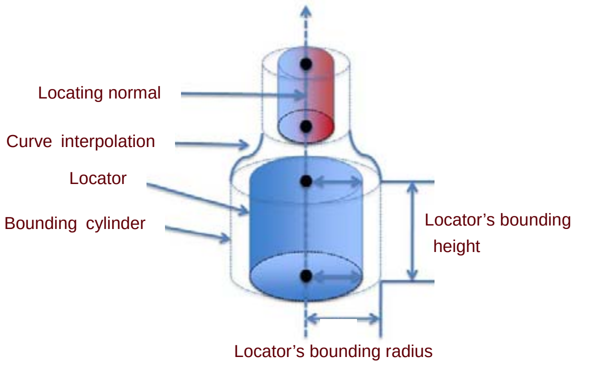

Figure 3 Proposed Integration approach of bounding cylinder and curve interpolation for extending the series of inter-disconnected cylinders.

The steps involved in this study are as following:
Step 1: The series of disconnected neuron morphology are bounded by another (bigger) cylinder.
Step 2: The curve interpolation points are calculated between two endpoints of bounding but adjacent cylinders.
Step 3: Curves are then fitted by interconnecting predetermined control points between bounding cylinders for wrapping the neuron segment to produce smoother connection and effective realism.

The bounding cylinder model

The model employs the use of cylinder containing the disjointed neural objects defined by enclosing the surface of the neuron morphology connection. This technique uses the geometric information about the faces, edges and vertices of data objects with the topological data on how these neural components are connected. To implement the algorithm, the complicated locator geometry must be simplified for rapid evaluation. Here, the bounding cylinder is used to represent locator. Each locator is described using three parameters defined as follows:
(1) Locator's bounding height: The locator's bounding height is the distance from the locating position P1 along the surface to position P2 normal to it. The P1 and P2 refer to extracted neuron digitalization coordinate <XID(n), Y ID(n), Z ID(n)> and <X C(n), Y C(n), Z C(n)> respectively an example is shown in Figure 4.
(2) Locator's bounding radius: The accessible radius locator's bounding radius is defined as if a cylinder is constructed using the locating position's normal as the cylinder axis, and the satisfactory accessible height as the cylinder height, the accessible radius locator's bounding radius is the maximal radius the cylinder can be constructed without interface with the work piece geometry. The locator's bounding radius is total additional length of neuron's radius (RID(n)) as illustrated in Figure 5.

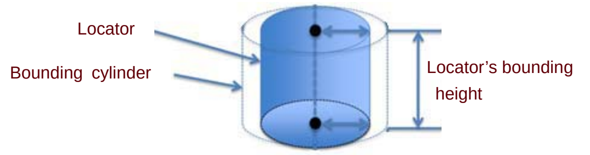

Figure 4 Illustration of locator's bounding height, the length of neuron segment (or known as locator) from start coordinate to end coordinate.

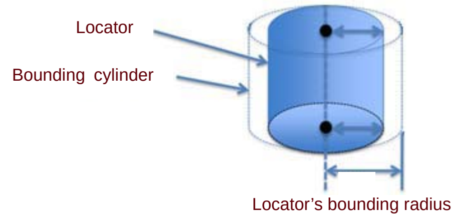

Figure 5 Illustration of locator's bounding radius (RL), the radius of cylinder bounding the neuron segment (also known as locator).

(3) Locator's curve interpolation: From the above definitions, and at a given locating position, a cylinder can be constructed using the accessible height locator's bounding height and the accessible radius locator's bounding radius. This cylinder illustrates the volume in three-dimension that can be accessed by a locator curve interpolation locator's curve interpolation, this is called "accessible cylinder". The volume of the accessible cylinder[33] is essential for evaluating the accessibility of certain position, and its relation with the locator's bounding cylinder determines the accessibility.

The proposed curve interpolation approach for enhancing neuron connection nodes

From Figure 3, at any given locating position, boundary of two segments (P_i and P_j) will be connected using the proposed curve interpolation model presented in Figure 6. This model is introduced to assist in describing the slight and sharp bends between adjacent nodes. This has been found to result in near-exact geometrical reconstruction of the neural model[34]. Because the neural segments are generally not likable to smooth cylinders with constant diameters and branches[35], it is only reasonable to make approximations of these with "straight segments". This is because the cylindrical fits could precisely describe the midline of neuronal structures by approximating the actual run of the surface of the neuron without giving good boundary definition for the non-tubular structures.

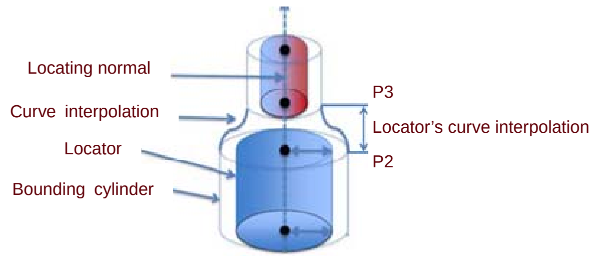

Figure 6 Illustration of Locator's curve interpolation bounding the neuron segment (also known as locator).

To achieve effective realism therefore, three points are chosen as the loci of the curve's path describing locator's curve interpolation (Figure 7).

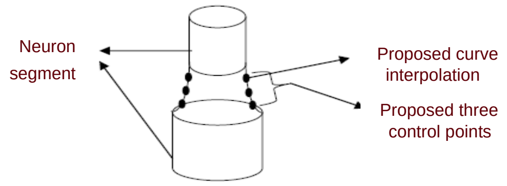

Figure 7 Proposed curve interpolation model.

Each locus is calculated by finding midpoint (Pm (n)) between two identified control points. As an example, the first locus is the midpoint between coordinate P1 and coordinate P2. After Pm (n) has been found, the step is repeated by applying Newell's formula (Equation 1) to find second and third midpoints (loci) between the coordinates P1 and P2. The second locus, Pm(n+1), is calculate between coordinate Pm(n) and coordinate P1, and the third, Pm(n+2), is calculated between coordinate Pm(n) and coordinate P2. A curve is then fitted to connect these loci together to form a single continuous curve. This algorithm returns points along the curve that passes exactly through the loci at specific instances to form smooth curve for points in between them. This is more or less like a "line-like" or "stick-line" 1D representation. It however captures the essential topology of the underlying neural object in an easy to understand and very efficient way.

The model visualization[35]

Gouraud shading (GS) technique is applied to the neuron surface visualization in order to achieve realism at the connective edges and bounding surface without undergoing the accompanying heavy computational requirement of calculating lighting for each pixel at vertices. This approach was applied because it was able to provide the objects (*i.e*. the series of cylindrical that acts as the neuron morphology) connection toward effective realism. Comparison between curved surface rendering using Flat Shade Polygons and the Gouraud shading is shown in Figure 8.

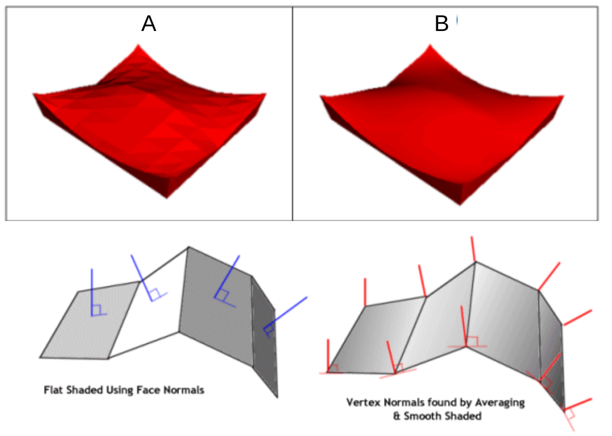

Figure 8 Comparing effects using (A) Flat shaded polygons and (B) gouraud shading[36].

GS that is also called intensity interpolation provides a way to display smooth shaded polygons by defining the RGB colour components of each polygon vertex based on the colour and illumination to eliminate intensity discontinuities. GS is the simplest rendering method and it computes faster than Phong shading without producing shadows and reflections.

In order to compute the intensity at a vertex, it is necessary to know the unit normal vector at the vertex. Since each vertex may belong to many polygons, first, Newell's formula[37] (Equation 1) is used to calculate the unit normal for each polygon containing the vertex (Ron Goldman).

$$N = \sum_{k=0}^{n} P_k \times P_{k+1} \qquad \{P_{n+1} = P_0\} \qquad (1)$$

Then, the unit normal vector is calculated by averaging the unit normal of the polygons containing the vertex:

$$N_{vertex} = \frac{\sum_{vertex \in Polygons} N_{polygons}}{\left|\sum_{vertex \in Polygons} N_{polygons}\right|} \qquad (2)$$

Finally, equation 3 is applied to compute the intensity at the vertex.

$$I_{uniform} = \underbrace{I_a k_a}_{ambient} + \underbrace{I_p k_d (L \bullet N)}_{diffuse} + \underbrace{I_p k_s (R \bullet V)^n}_{specular}, \qquad (3)$$

IMPLEMENTATION AND RESULTS

The developed prototype is presented in this section for reconstructing neuron morphological model from digitalized neuron data. The whole process is automated but it has also been adapted to be dynamically manipulated by the user.

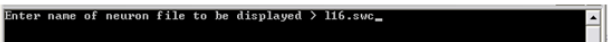

Figure 9 System interface for Action-User key-in neuron file morphologies from format SWC.

After responding correctly to the interface, three-dimensional scene is loaded using OpenGL for previewing the representation neuron. OpenGL has been chosen to create the model since it significantly speeds up rendering and real-time visualization[38]. When a neuron data is loaded, the proposed reconstruction model is generated from the object's component traces and the model is rendered using the GS approach. One of the results produced from the prototype as well as the outcome after manipulating the neuron representation (such as zooming and rotating) are shown in Figure 10.

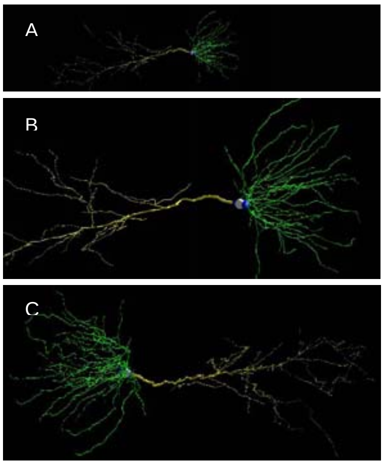

Figure 10 Result of neuron presentation and its manipulation (rotate and zoom).

(A) Neuron morphology reconstruction.

(B) Neuron presentation after zoom up to 12 times.

(C) Neuron presentation after rotate and zoom up to three times.

The zooming could be extended up to 21 times than the original view. The result after implementing Gouraud Shading into enhanced reconstruction neuron model is shown in Figure 11.

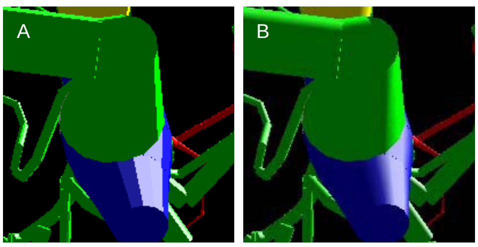

Figure 11 Comparison of neuron reconstruction model produced (A) without Gouroud shading and (B) with Gouraud shading (Note the effects at the neuron segments connections).

This combination approach is able to provide opportunity to explore connectivity of the neuron segments. It is anticipated that this finding could be helpful for the researchers and to whosoever may have keen interests in exploring the ideas of neuron reconstruction and visualization[39].

User acceptability

A survey was conducted on a group of bioinformatics analysts, the findings show that most of them are not exposed nor have experience of neuron data, model, visualisation and system/applications. The result shows that 82% of the respondents do not have any experience in manipulating neuron data and its application. The result is shown in Figure 12.

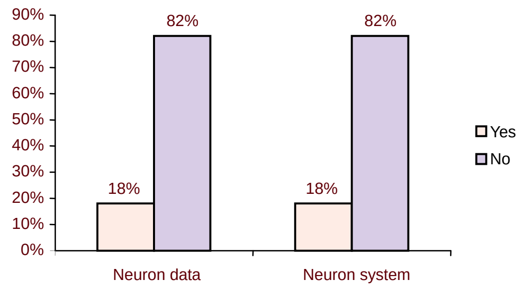

Figure 12 Survey on users' experience in manipulating neuron data and system.

However, 100% is recorded about the need that neuron data are necessary to be visualized in three-dimension. The percentages of characteristics by choice in terms of individual consideration for the acceptability are presented in Figure 13. Based on result shown in Figure 13, the highest element to consider for development of neuron visualization is the realistic aspect in neuron model presentation. About 82% of the respondents agreed that the result from this proposed model is able to visualize neuron data in three-dimension more effectively for intuitive data explorations. Most respondents agreed that with this model, coloration of the pigments is very helpful in differentiating connected segment of the neuron model which makes visualization very intuitive. The other strengths are as shown in Figure 14.

From the selected users' feedback, the proposed prototype achieves an average performance and aligns with existing neuron applications' requirement. This is measured in term of user satisfaction in interacting with developed prototype. The proposed neuron model is similar with the original (biological) neuron and presentation of different colours that was used to differentiate neuron connection types. The overall result of user acceptance and satisfaction towards developed prototype is described in Figure 15. The lower rating starting from 1 indicated as a low performance achievement to the highest performance with rating indicated as 5.

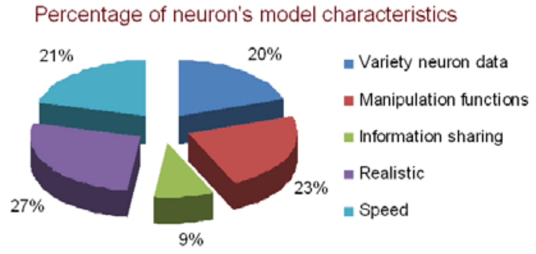

Figure 13 Individual perception of the necessity for neuron visualization by percentages.

Figure 14 User's feedback on advantage or strengths obtained from prototype development.
(1) Manipulation functions for viewing neuron model from different angles. (2) Different colour presentation for differentiating connected segments of neuron model. (3) Focus on specific neuron data for visualization and comparison *i.e*. usage of neuron SWC data.

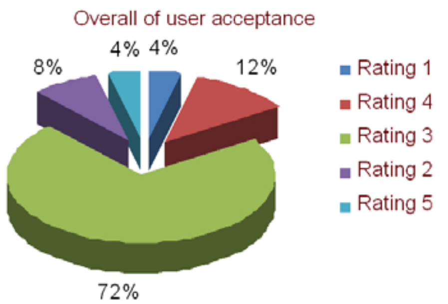

Figure 15 Overall feedback on performance achievement of the proposed model.

DISCUSSION

This paper presents a simplified prototype for constructing neuron structures with properties closely matched with three-dimension neuronal morphology and connectivity. The generated model is wrapped by integrating bounding cylinder and the proposed curve interpolation methods to achieve an enhancement of the appearance of disconnected neuron segments. The model's surface at these connection points is rendered using Gouraud shading technique which provides smooth neuron connection and produces a more realistic appearance of the neuron. Gouraud shading techniques is embedded in the visualization application. The essence of using this shading technique is to achieve smooth appearance of polygonal model by reducing the impact of sharp edges to provide the human eye the impression of smooth curved surfaces of the connected neuron segments.

When the algorithm is used to detect and display soft issues such as the neuron cells, the algorithm tends to be more cumbersome. Although, it is still able to produce useful displays of the three-dimension neuron images. The time required to segment the volume, isolate the desired surface (as is required by any three-dimension surface display) are greatly enhanced by this proposed model. However, it seems less suitable to be applied on its own (singularly) for anatomical structure visualization (*i.e*. neuronal morphology). Thus, in a forward way, the introduction of more adaptive algorithm to handle these situations is the next focus of our research.

CONCLUSION AND FUTURE WORKS

This research presents a clue to achieve better and improved realism in neuron model rendering. Hopefully, this model can be used to improve the appearance of the neuron morphology, connections and diagnosis of the entire central nervous system. In the near future, the model could be further enhanced by applying polynomial function. This function is used to estimate accurate curve interpolation points to produce neuron model which could increase smoothness of the connection model as well as rendering realisms.

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Conflicts of interest: No declared.

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