MAGNITUDE-BASED STREAMLINES SEED POINT SELECTION FOR UNSTEADY FLOW VISUALIZATION

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DEDICATION

Praise to Allah SWT for the guidance, strength, power of mind, protection and skills and for giving us a healthy life, sustenance and knowledge.

To my father, mother, thanks for keep praying for me to finish this long journey.

Lastly, to my wife, daughters and son, this thesis is dedicated to you all.

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ABSTRACT

Flow visualization is a method utilized to obtain information from flow data sets. Proper blood flow visualization can assist surgeons in treating the patients. However, the main problem in visualizing the blood flow inside the aorta is the unsteady blood flow rate. Thus, an unsteady flow visualization method is required to show the blood flow clearly. Unfortunately, streamlines cannot be used by time-dependent flow visualization. This research aims to propose an improvement for the current streamline visualization technique and appearance by implementing an improved streamline generation method based on structured grid vector data to visualize the unsteady flow. The research methodology follows a comparative study method with the Evenly-Spaced Seed Point placement (ESSP) method as the benchmark. Magnitude-Based Seed Point placement (MBSP) and selective streamlines enhancement are introduced to produce longer, uniform, and clutter-free streamlines output. A total of 20 visualization results are produced with different streamlines separation distance. Results are then evaluated by comparing streamlines count and uniformity score. Subsequently, survey and expert reviews are carried out to strengthen the analysis. Survey questions are distributed to respondents that have data visualization knowledge background in order to get feedback related to streamlines uniformity and enhancement. In addition, experts review is conducted to get feedback based on current researches and techniques utilized in the related fields. Results indicate that streamlines count for MBSP are higher, but the differences are neglectable. Uniformity analysis shows good performance; with 80% of the MBSP results have better uniformity. Survey responses show 65% of respondents agreed MBSP results have better uniformity compared to ESSP. Majority of the respondents (92%) agreed that selective streamlines is a better approach. Experts review highlights that MBSP can distribute streamlines better in 3-dimension space compared to ESSP. Two significant findings are identified in this research: magnitude is proven to be an important input to locate seed points; and selective streamlines enhancement is a more effective approach as compared to global streamlines enhancement.

ABSTRAK

Visualisasi aliran adalah kaedah digunakan untuk mendapatkan maklumat dari data aliran. Visualisasi aliran darah yang betul dapat membantu pakar bedah dalam merawat pesakit. Namun, masalah utama dalam visualisasi aliran darah di dalam aorta adalah kadar aliran darah yang tidak stabil. Justeru, kaedah visualisasi aliran tidak tetap diperlukan untuk menunjukkan aliran darah dengan jelas. Malangnya, kaedah garis arus tidak dapat digunakan oleh visualisasi aliran bersandar masa. Tujuan penyelidikan ini adalah untuk mencadangkan penambahbaikan pada teknik visualisasi dan penampilan garis arus menggunakan kaedah penjanaan garis arus yang lebih baik berdasarkan data vektor grid berstruktur untuk memvisualisasikan aliran tidak stabil. Kaedah kajian perbandingan digunakan dalam kajian ini dengan teknik penempatan Titik Punca Sama Jarak (ESSP) sebagai penanda aras. Penempatan Titik Punca Berasaskan Magnitud (MBSP) dan panambahbaikan garis arus terpilih diperkenalkan untuk menghasilkan garis arus yang lebih panjang, seragam, dan kemas. Sejumlah 20 visualisasi dihasilkan dengan jarak pemisahan yang berbeza. Hasil dinilai dengan membandingkan kiraan garis arus dan skor keseragaman. Tinjauan dan ulasan pakar dilakukan untuk memperkukuhkan analisis. Soalan tinjauan diedarkan kepada responden yang mempunyai latar belakang pengetahuan visualisasi data untuk mendapatkan maklum balas yang berkaitan dengan keseragaman dan penambahbaikan garis arus. Tinjauan pakar dilakukan untuk mendapatkan maklum balas berdasarkan penyelidikan dan teknik terkini yang digunakan dalam bidang yang berkaitan. Dapatan kajian mendapati kiraan garis arus untuk MBSP adalah lebih tinggi, tetapi perbezaannya tidak ketara. Analisis keseragaman menunjukkan prestasi yang baik, dengan 80% hasil visualisasi MBSP mempunyai keseragaman yang lebih baik. Tinjauan juga menunjukkan 65% responden bersetuju hasil MBSP mempunyai keseragaman yang lebih baik berbanding ESSP. Majoriti responden (92%) bersetuju penambahbaikan garis arus terpilih adalah pendekatan yang lebih baik. Ulasan pakar mendapati MBSP dapat mengedarkan garis arus lebih baik dalam ruang 3 dimensi berbanding ESSP. Dua penemuan penting telah dikenal pasti dalam penyelidikan ini: magnitud adalah terbukti sebagai input penting untuk mencari titik punca; dan penambahbaikan garis arus terpilih adalah pendekatan yang lebih berkesan berbanding dengan penambahbaikan garis arus global.

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LIST OF ABBREVIATIONS

AAA - Abdominal Aortic Aneurysm
MRI - Magnetic Resonance Imaging
CT - Computed Tomography
US - Ultrasound
GPU - Graphic Processing Unit
RAP - Repeated Asymmetric Patterns
PIV - Particle Image Velocimetry
echo-PIV - Echocardiography PIV
CTM - Cyclic Texture Mapping
GFS - Global Forecast System
NOAA - National Oceanic and Atmospheric Administration
ERDDAP - Environmental Research Division’s Data Access Program
MSE - Mean Square Error
GFS - Global Forecast System
CSV - Comma
MBSP - Magnitude Based Seed Point
ESSP - Evenly Spaced Seed Point

LIST OF SYMBOLS

φ - Distance Function

G - Contour

v - Velocity

° - Degree

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Flow visualization is important in conveying information to viewers. There are many ways to get blood flow information from medical imaging techniques and simulation process (de Hoon *et al.*, 2014). The current available techniques allow researchers and clinicians to get up in time-varying as well as field of volumetric vector. Although the trend of blood flow visualization focuses more on four dimensional visualization, these data are not yet analysed extensively because the normal procedures of inspection is not enough to extract useful information (Pelt and Vilanova, 2013). Past clinical research conducted by researchers and clinicians have proved that medical conditions are also affected by a distinctive blood flow. An irregular blood flow indicates that there is a possibility of changes in the nearby wall structure. Even a small change of tissues can affect the blood flow which leads to a worsening effect of the disease (Peiffer *et al.*, 2013).

It is important to have a strong foundation in a scientific visualization body of knowledge before going through the technical details of flow visualization. Figure 1.1 shows the knowledge domain of scientific visualization extracted from the Association for Computing Machinery computing classification system. Scientific visualization which falls under computing methodologies can be derived into two categories, namely volume visualization and flow visualization. This research is focused on the flow visualization technique throughout the process of problem formulation up until research contribution.

1.1 Problem Background

Knowledge on blood flow has been used in the diagnosis and prognosis of the patients. It also has a decisive role in evaluating cardiovascular diseases, especially in cardiac ischemic disease which is caused by a lack of blood supply to the heart muscle. Instead of using blood flow information, clinicians prefer to evaluate patients using medical image modalities acquired from Magnetic Resonance Imaging (MRI), Computed Tomography (CT), or Ultrasound (US) (Doost *et al.*, 2016). These images can provide information related to the morphology of patient anatomy. Blood flow data from specific patients are normally not analysed since clinicians are more focused on the heart muscle activity.

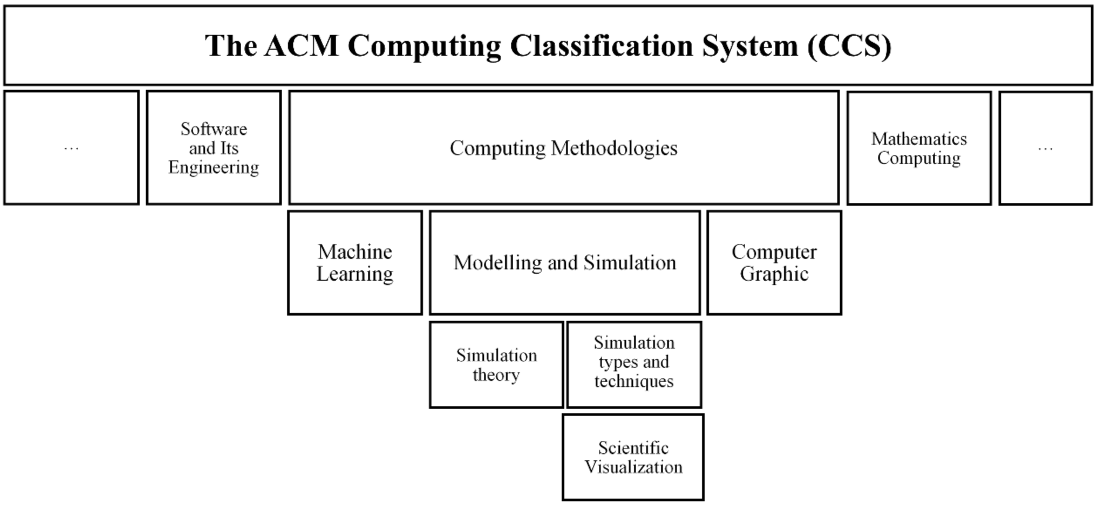

Figure 1.1 Knowledge domain of scientific visualization

Current computer simulation and flow visualization techniques can provide time-varying blood flow velocity fields with remarkable quality. A combination of phase-contrast MRI and computational fluid dynamic knowledge can provide a velocity of volumetric data within the heartbeat cycles. Other research in blood flow visualization technique is evolving fast from two-dimensional to three-dimensional, and currently there are extensive studies in four-dimensional flow visualization (Markl *et al.*, 2012). The results of these research allow clinicians to obtain more quantitative information and understand more complicated behaviours of blood flow.

Currently, there are extensive studies on medical images that are able to produce more multidirectional blood flow and velocity data. But understanding the data seems to be a problematic task for the physicians since these data covers a large and complex blood flow field. The common routine of physicians in analysing the blood flow is by mental reconstruction from the medical images, which require a lot of experience (van Pelt *et al.*, 2009). This technique becomes more challenging when studying a complex structure, especially related to the heart anatomy. Accumulating additional flow features such as time and flow direction will increase the difficulties in analysing traditional visualization results. In other words, visualizing large information in a single result will reduce the viewer's understanding.

Conveying too much information in a single visualization is not the best solution in minimizing the gap between information and the viewer (Ma, Wang, Shene, *et al.*, 2013). Therefore, a complete and modest flow visualization is needed to allow the viewer to understand and simplify the analysis process in a short period of time. The use of glyphs and streamlines need to be balanced to avoid unnecessary elements in the flow visualization result. These distinctive characteristics are important, especially in the field of medical imaging. Time usage is very important for clinicians in treating the patients. The flow visualization needs to be immensely effective, allowing physicians to analyse the patient-specific result in a short period of time.

One of the aims in visualization is to mimic the realism of the flow information. With the current available techniques such as velocity-encoded phase contrast MRI, blood flow information can be measured in multidirectional without the aid of contrast agents. It is recommended to be used for visualization of a large-scale flow pattern and analysing the flow for different cardiovascular segments. The drawback of using patient-specific data is that the MRI requires a longer time to obtain the information (Markl *et al.*, 2012).

There are many techniques available to visualize flow. Each person has their own preference in order to understand the flow (Tao *et al.*, 2014). Forcing viewers to understand the flow using certain methods may reduce the information gathered from the visualization. Clinicians who are familiar with phase contrast MRI or Doppler ultrasound may have a different preference compared to experts in the scientific visualization area. The knowledge gap between visualization experts and clinicians needs to be reduced to allow clinicians to grasp the rich information in flow visualization.

Flow can be visualized with different techniques (van Wijk, 2002; Garth and Tricoche, 2005; McLoughlin *et al.*, 2010). One of the conventional geometric-based techniques is to use streamlines to visualize flow. Streamlines are widely used to visualize any kind of flow from the provided vector dataset. The starting point of streamlines is basically called a seed point. The lines are generated based on the trajectories of the vector from the seed point. Thus, it is important to place the seed point at the correct location.

There are also problems regarding most of the seed point placement method. The initial seed point is placed randomly in the flow field which may neglect important flow information (Jobard and Lefer, 1997; Mebarki *et al.*, 2005). There are researcher studies on the method of placing the seed point to get more information from the same data (McLoughlin *et al.*, 2010). There are no major problems in plotting streamlines based on the seed point and velocity. The issue on this matter arises when the streamline technique is implemented to the unsteady flow since the velocity data changes over time.

Streamlines are known with features that are able to visualize flow patterns globally (Laidlaw *et al.*, 2001). It is the preferable method compared to image-based and texture-based because this method is easier to calculate and render at an interactive frame rate with different resolutions (Ma, Wang and Shene, 2013). The flow pattern is still and consistent when this method is applied in a steady flow. There are no extra frames in a steady flow since the vector data is the same throughout the time frame, but streamlines are not suitable to be used for an unsteady flow. An unsteady flow data consist of several frames, containing related vector information across the frames (Jobard and Lefer, 2000). Generally, streamlines can visualize any flow pattern provided by the vector data. But streamlines are not able to show the transition between time frames. The flow pattern for each time frame is different since the unsteady flow produces different vector data for each frame. This problem increases the difficulty for viewers to identify and analyze the information from an unsteady flow.

Seed point placement plays an important role in generating streamlines. Choosing a proper seed point in the flow is the first step before the integration process can be done. Several seed point algorithms such as farthest seed point (Mebarki *et al.*, 2005) or evenly spaced seeding (Jobard and Lefer, 1997) can be used to place and generate the streamlines based on viewer preference. These algorithms are suitable to be used with a steady flow field. Finding the correlated seed point between frames in an unsteady flow field is the main problem in streamlines. This is a major problem that can cause visual artefacts if it is not placed at the correct location.

There are three important criteria that need to be considered when using streamlines to produce a flow visualization result which are coverage, uniformity and continuity (Verma *et al.*, 2000; Rosanwo *et al.*, 2009). It is difficult to achieve all three criteria in a single result because there is a trade-off between those criteria. The current research challenge is to balance those criteria by generating enough streamlines to cover the visualization domain, even spaces between streamlines, and able to produce long streamlines in the visualization result (Hongfeng Yu *et al.*, 2012). This is crucial to ensure the visualization result is able to convey as much information as possible.

Apart from seed point placement, visual appearance plays an important role in providing additional information other than the streamlines flow pattern. Colours and glyphs are able to provide additional information which are not suitable to be conveyed by streamlines especially when related to scalar data. There are issues that require glyph usage in flow visualization results. A user study on flow visualization result shows that viewers have difficulties in identifying flow direction (Martin *et al.*, 2008). Thus, a solution is needed to incorporate streamlines and glyphs together to improve the direction information accuracy.

Colour usage has a significant impact in visualization results. It can be used to increase the attribute value in the visualization (Healey and Enns, 1999). Colour selection is important so that it is linearly separable when used on streamlines. The total number of base colours also contributes to the accuracy of the provided information. There are issues regarding colour usage in flow visualization. A wide range of similar attributes on a nearby focus area increases the time taken to identify the underlying information (Healey and Enns, 2012). This issue is more severe especially with uniform streamlines width. It also increases the time taken for visual search process map with the colour legend (Netzel *et al.*, 2017).

1.2 Problem Statement

Seed point placement gives a huge impact on the final output of flow visualization using streamlines (McLoughlin *et al.*, 2010; Lawonn *et al.*, 2018). Most of the methods (Turk and Banks, 1996; Jobard and Lefer, 2000; Garth and Tricoche, 2005; Liu *et al.*, 2006) place the initial seed point randomly at first before applying the proposed method of placing the seed point. The initial process of choosing the seed point location is very important to highlight the critical point in the vector field domain. Other methods may place the seed point during their algorithm execution, but this may limit the streamlines length based on the streamline stopping rules as there are streamlines generated from past iterations. Using a template to place the seed point in a critical point area is able to produce uniform streamline patterns but it cannot produce evenly spaced streamlines caused by the seeding placement template. Tracing streamlines is also one of the on-going issues in flow visualization especially in an unsteady flow where flow patterns changes over time. Dense streamline placement produces rich information results but increases in difficulty to trace streamlines. On the other hand, sparse streamline placement allows easier streamlines tracing, but the visualization results may not be able to provide detailed information about the flow field. Colour and glyph usage also need to be analysed to avoid unnecessary enhancement in the visualization results. It is important to carefully choose and enhance the streamlines presentation to overcome these problems. Streamline candidates can be obtained from the initial seed point because of its importance and criteria. Thus, an improved seed point placement is needed to solve the initial seed point placement issues as well as streamline selection for streamline enhancement for blood flow visualization.

1.3 Research Question

The research questions can be derived from the problem statement in this research.

(a) How to place the initial seed point to improve uniformity in the visualization result?
(b) How to enhance the streamlines visual presentation in both 2D and 3D flow visualization?
(c) How to incorporate an improved seed point placement with streamline enhancement in 3D blood flow visualization?

1.4 Aim of Research

To propose an improvement for the current streamline visualization technique by implementing an improved seed point placement with enhanced streamlines presentation to visualize unsteady blood flow in the aorta.

1.5 Aim of Research

To achieve the aim, the following research objectives are formulated:

(a) To define a new selection scheme in locating the initial seed point for the streamlines.
(b) To propose a streamline enhancement method based on colour, size, and glyph properties.
(c) To visualize the proposed method with animation in time series data for an unsteady flow visualization.

1.6 Research Scope

There are several scopes defined in this research. The scopes are divided into data, tools and software. The first scope is the type of medical images used in this research. Patient information meta data in the medical images were stripped off to avoid any information breach. Medical images were obtained from a CT-scan procedure which focused on the torso region of the patient. The structure of the aorta and aneurysm should be included in the CT scan result. The second scope is the tools used in this research. Several tools were used in this research to conduct specific tasks which are not covered in this research. The first tool is SimVascular. It is used for surface extraction and to conduct flow simulation. The second tool used is Paraview which is specialized for scientific visualization. The last scope is software. The software used in this research are for vector generation and algorithm implementation. Wolfram Mathematica and MathWorks MATLAB are chosen for these tasks as they provide built-in functions for complex mathematical operations.

1.7 Significance of Research

A new seed point selection scheme will produce longer streamlines, allowing viewers to observe flow patterns at a specific area. This will help researchers to understand the behaviour of blood flow inside an aorta with the presence of aneurysm. Location with a high flow velocity will display longer streamlines as new schemes will be developed based on the magnitude. Visual enhancement will produce distinctive streamlines which highlight more information at important regions in the visualization results.

Animating streamlines feature is very important to visualize an unsteady flow. Realizing this feature will allow researchers to observe and study the transition of blood flow inside the aorta at full length rather than study the flow progress by frames using the pathlines or streaklines method. Fusing these two features will be able to improve the flow visualization result as more information can be obtained in a short amount of time.

1.8 Thesis Structure

This thesis consists of seven chapters. The first chapter allows the reader to grasp the basic idea about the research problems, aim and objectives. Chapter 2 focuses on the literature review that covers fundamental knowledge on flow visualization, medical image modalities, and recent research findings related to the research. Chapter 3 describes the research methodology used in this research to achieve the objectives. Chapter 4 explains the approach and implementation of seed point placement. Chapter 5 elaborates on the approach to enhance the streamline presentation. Chapter 6 details the evaluation and analysis of the proposed technique, and comparison between the proposed technique with the current available technique. The last chapter concludes the thesis content and contribution, proposed algorithm limitation, and future research work and direction.

1.9 Summary

Visualization in the medical area has been assisting humans a lot in studying the causes of diseases. This research aims to improve the visualization method by introducing new seed point placement, enhance streamline presentation, and animate the streamlines method to visualize unsteady blood flow. A computer-generated visual representing the aorta will be produced with blood flow visualization. 3D visualization will allow doctors and surgeons to study the blood flow inside the aorta in an effective way, helping them to plan for further steps in treating patients.

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