INVESTIGATION OF EXCITATION COILS CONFIGURATION AND PARTICLE SWARM OPTIMIZATION OF COIL'S DIAMETER IN MAGNETIC NANOPARTICLES IMAGING

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ABSTRACT

Magnetic Nanoparticles Imaging (MNI) is a new imaging method which uses magnetic nanoparticles as the contrast agent. The superparamagnetism of ferro- and ferrimaterial allowed the particles to act as a temporary magnet when an external excitation is applied. The imaging is based on the reconstruction of the measured relaxation time (magnetorelaxometry) from the sample by SQUID sensors after the applied field is switched off. To date, the imaging method is still not applicable on human due to many undetermined parameters of the diagnostic configuration. The equation of the reconstruction is generally ill-posed due to the involvement of many parameters in the configuration. Hence, the optimization is required in order to eliminate the unstable parameters of this imaging technique. In this thesis, the study of excitation coils' configuration has been conducted with manipulation of the number coils, arrangement of coils, diameter of coils and the shape of coils. The results show that by increasing the number of coils will improve the correlation coefficient of the reconstruction. However, due to the limitation of the grid size, the size of the coils is another concerned criterion; hence, the total area of the coils in each grid must be smaller than the area of the grid. The correlation coefficients of the reconstruction with varying the coils diameters show an improvement with smaller coils diameter. This observation obeyed the algorithm of diameter optimization in this thesis. Besides, the examinations of the arrangement and shape of coils show that both these criteria are highly depending on the shape of the sample. Due to the size of the rectangular coils used in the simulation are basically larger than the circular coils, hence, better results are found in the circular coils. On the other hand, the examination of the possibility of applying particle swarm optimization (PSO) method on the coils diameter has been studied by constructing the algorithm of the magnetic field calculation. The results of the algorithm construction showed that the diameter element is a non-linear parameter, and it is not suitable to be used in PSO as this method only applicable for the element which poses a linear relationship between the element and the output of optimization.

ABSTRAK

Pengimejan nanopartikel magnetic merupakan sejenis teknik pengimejan baru yang menggunakan nanopartikel magnet sebagai agen perbandingan. Sifat *superparamagnetism* bahan *ferro*- dan *ferri* membolehkan partikel-partikel berfungsi sebagai magnet sementara apabila pengujaan luaran diapplikasikan. Pengimejan ini beroperasi berdasarkan konsep pembinaan semula tempoh pengenduran (magnetorelaxometry) yang diukur dengan menggunakan penderia SQUID selepas pengujaan luaran dimatikan. Sehingga kini, teknik pengimejan ini masih tidak dapat dipraktikkan pada tubuh manusia disebabkan masih terdapat banyak parameter konfigurasi diaognostik yang belum dapat dikenal pasti. Secara umumnya, persamaan matematik yang digunakan untuk membina semula imej masih belum terumus dengan baik disebabkan oleh penglibatan terlalu banyak parameter di dalam konfigurasi tersebut. Oleh yang demikian, proses pengoptimuman adalah sangat penting bagi menghapuskan parameter yang tidak stabil di dalam teknik pengimejan ini. Oleh yang demikian, tesis ini membentangkan satu kajian mengenai konfigurasi gegelung medan pengujaan dengan memanipulasikan bilangan, susun atur, diameter dan bentuk gegelung pengujaan. Keputusan kajian ini menunjukkan bahawa, pertambahan bilangan gegelung pengujaan akan meningkatkan pekali korelasi pembinaan semula. Namun begitu, disebabkan oleh limitasi pada saiz grid, saiz pada gegelung pengujaan menjadi kriteria yang turut perlu diteliti; oleh itu, jumlah permukaan gegelung dalam setiap grid mestilah lebih kecil daripada permukaan grid tersebut. Pekali korelasi daripada simulasi dengan pelbagai diameter gegelung menunjukkan peningkatan dengan penggunaan diameter lebih kecil. Pemerhatian ini juga turut mematuhi konsep algoritma optimasi yang diulaskan dalam tesis ini. Selain itu, kajian terhadap susun atur dan bentuk gegelung pengujaan mendapati kedua-duanya sangat bergantung kepada saiz gegelung tersebut. Disebabkan saiz gegelung segi empat yang digunakan dalam simulasi ini lebih besar berbanding saiz gegelung bulat, maka, keputusan yang lebih baik dijumpai pada gegelung bulat. Selain itu, potensi pengaplikasian kaedah *particle swarm optimization (PSO)* pada diameter gegelung juga telah dikenalpasti dengan pembinaan semula algoritma pada pengiraan medan magnet. Hasil daripada algoritma itu menunjukkan bahawa elemen diameter merupakan parameter yang tidak linear, dan ianya tidak sesuai digunakan dalam *PSO* kerana kaedah ini hanya terpakai untuk elemen yang mempunyai hubungan linear diantara elemen tersebut dan hasil optimasi.

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LIST OF ABBREVIATIONS

STM	-	Scanning Tunneling Microscope
AFM	-	Atomic Force Microscope
MNP	-	Magnetic nanoparticles
MPI	-	Magnetic Particle Imaging
MRI	-	Magnetic Resonance Imaging
MNI	-	Magnetic Nanoparticles Imaging
(U)SPIO	-	(Ultrasmall) Superparamagnetic Iron Oxide nanoparticles
MRX	-	Magnetorelaxometry
ACS	-	Alternating Current Susceptometry
SQUID	-	Superconducting Quantum Interference Device
L	-	Lead Field Matrix
TSVD	-	Truncated Singular Value Decomposition
PSO	-	Particle Swarm Optimization
GBEST	-	Global Best
LBEST	-	Local Best

LIST OF SYMBOLS

τ_N	-	Néel relaxation time
τ_0	-	Time characteristic of probed material
ΔE	-	Energy barrier threshold for the magnetization flip
k_B	-	Boltzmann constant
T	-	Temperature
τ_m	-	Measured time
τ	-	Relaxation time
T_B	-	Blocking temperature
T_C	-	Currie temperature
K	-	Anisotropy constant
V_p	-	Particles volume
$\vec{n}$	-	Particle preferred direction
$\vec{m}$	-	Particle magnetic moment vector
τ_B	-	Brownian relaxation time
η	-	Viscosity of the carrier liquid
V_{hydr}	-	Hydrodynamic volume
τ_{eff}	-	Effective time constant
$\overrightarrow{B_{exc}}$	-	External magnetic field
t_{exc}	-	Excitation time
t_{del}	-	Delay time
t_{mag}	-	Magnetization time
r	-	Distance from magnetic source
$\vec{H}$	-	Magnetic field
χ_v	-	Isotropic magnetic volume susceptibility

N_p	-	Concentration of the nanoparticles
μ	-	Magnetic moment of a single particle
$\delta\vec{m}$	-	Dipole moment
δV	-	Volume element
$\vec{r}$	-	Voxel location vector
$\vec{r_s}$	-	Sensor location vector
$\delta\vec{B}$	-	Dipole field
d_i	-	Unity vector
m_i	-	Magnitude of unity vector
$\vec{w_j}$	-	Weight of j-th sensor
$\vec{d_j}$	-	Direction of j-th sensor
$\vec{b_f}$	-	Forward computed field
$\vec{b_m}$	-	Measured field
L^T	-	Transpose of lead field matrix
L^+	-	Pseudo inverse of L
σ_r	-	Regularization parameter
$\vec{I}$	-	Current
A_1	-	Relation of $\vec{I}$ to $\vec{H}$
$\vec{a}$	-	Position vector of initial point of line segment
$\vec{b}$	-	Position vector of end point of line segment
$\vec{r_0}$	-	Position vector of voxel
$\vec{r_1}$	-	Vector from $\vec{a}$ to $\vec{r_0}$
$\vec{r_2}$	-	Vector from $\vec{b}$ to $\vec{r_0}$
S	-	Sensitivity
A_2	-	Relation of $\vec{H}$ to $\vec{S}$
E_3	-	Identity matrix
c	-	Physical environment constant
$\vec{p}_{Best}$	-	Local best position
$\vec{p}_{GlobalBest}$	-	Global best position
f_{Best}	-	Local best function
$f_{GlobalBest}$	-	Global best function
$\vec{v}$	-	Velocity vector

$\vec{p}_{Current,i}$	-	Current position
$\vec{p}_{Current,i+1}$	-	Position of next iteration
$\vec{r}_{Cognitive}$	-	Entry vector
$\vec{r}_{Social}$	-	Entry vector
$w_{Inertia}$	-	Previous iteration weighting factor
$w_{Cognitive}$	-	Next iteration weighting factor
w_{Social}	-	Current iteration weighting factor
$nBest(i)$	-	Neighbor best position
θ_s	-	Angle between segmented lines
d	-	Diameter
$\vec{r}_c$	-	Position vector of coil
$\overrightarrow{r_v}$	-	$\overrightarrow{r_c} - \overrightarrow{r_0}$

CHAPTER 1

INTRODUCTION

1.1 Background of study

Nanotechnology or nanotech is a technology which manipulates the matter on an atomic, molecular and supramolecular scale. It expresses the billionth part of unit, which a nanometer is the 10^{-9} –th part of a meter. Nanotechnology is defined by its abilities to manipulate the matter with dimension sized from 1 nm to 100 nm and comprises the development of materials within this range of sizes. The functionality in a smaller space allowed the application of this technology across other science fields, such as chemistry, biology, physics, materials science, and engineering.

The concepts of nanotechnology were first discussed by Richard Feyman, a renowned physicist in 1959. Feyman described the possibility of synthesis via direct manipulation of atoms in his talk "There's Plenty of Room at the Bottom" [1]. This idea then inspired Eric Drexler, which independently used the term "nanotechnology" in his book "Engines of Creation: The Coming Era of Nanotechnology". In his book he proposed that the idea of a nanoscale "assembler" which would be able to build a copy of it and of other items of arbitrary complexity with atomic control [2]. At the same time, Gerd Binnig and Heinrich Rohrer at IBM Zurich Research Laboratory invented the Scanning Tunneling Microscope (STM), which provided unprecedented visualization of individual atoms and bonds. This technology successfully used by the researchers to manipulate individual atoms. Unfortunately, STM has some limitations such as only works for conducting materials [3]. However, these limitations were then eliminated by the invention of Atomic Force Microscope (AFM) [4]. In the early 2000s, the field garnered increased scientific, political, and commercial attention that to both controversy and progress. The definitions and potential implications of nanotechnologies were questioned in the report of Royal Society. Challenges were raised regarding the feasibility of applications envisioned by advocates of molecular nanotechnology [5].

The great achievement in nanotechnologies had led a growth in medical field. The development of a wide spectrum of nanoscale technologies is the key to change the foundation of pathologies diagnosis, treatment and prevention. National Institutes of Health (Bethesda, MD, USA) referred these technologies as nanomedicines. Nanomedicines have the ability to transform molecular discoveries arising from genomics and proteomics into widespread advantage for patients. The subject area of nanomedicine is large and includes nanoparticles, biological mimetics (e.g., functionalized carbon nanotubes), “nanomachines” (made from interchangeable DNA parts and DNA scaffolds), nanofibres and polymeric-nanoconstructs (molecular self-assembly peptides for tissue engineering) nanoscale microfabrication-based devices (silicon microchips), sensor and laboratory diagnostics. Besides, there is a huge interest of studying the capability of nanoscale technologies in cells targeting in the body for drugs, genetic materials and diagnostic agents delivery [6]. Therefore, study into the biocompatible delivery and targeting of pharmaceutical, therapeutic, and diagnostic agents through intravenous and interstitial routes of administration with nanosized particles is at the forefront of concerns in nanomedicine.

The discovery of nanoparticles provided wide possibilities of application in nanomedicine. Gold nanoparticles have been used as quenchers in fluorescence resonance energy transfer measurement studies. The unique behavior of gold nanoparticles in the distance-dependent optical property has enabled the evaluation of binding of DNA-conjugated gold nanoparticles to a complementary RNA sequence [7]. The wide use of iron oxide cored nanocrystals with superparamagnetic properties as the contrast agents in magnetic resonance imaging (MRI) is another evidence of rising of nanotechnologies in medicines.

Magnetic Nanoparticles Imaging (MNI) is a tomographic imaging method which uses nanoparticles as the contrast agent to measure the magnetic field. This concept was proposed by Gleich and Weizenecker in 2005 as a novel imaging modality [8]. They suggested that ferromagnetic nanoparticles have the potential to provide quantitative three-dimensional real-time imaging with high sensitivity and spatial resolution, based on the non-linear magnetization and saturation behavior of ferromagnetic materials. Therefore, this method shows a high potential as an imaging modality for biodistribution of magnetic nanoparticles. However, only the setups with small sample volumes have been designed and presented up to now. A large fields will be required if it is designed for human. Additionally, scaling and realization of clinical scanners requires a vast amount of work and future developments. The single-sided of MNI device shows the results of considerable decrease image quality [9]. Similar to MRI, MNI does not allow for binding specific detection with the current technology.

1.2 Problem Statement

The reconstruction results from previous finding show that there are a lot of unsure elements in either setups or configurations of the imaging methods. The results of reconstruction either by homogeneous excitation field or inhomogeneous field do not provide promising results. This imperfection has triggered the studies of simulation configurations and reconstruction methods in order to obtain an optimum result. Previous works on optimization of currents flow through the excitation coils contributed in enhancing the reconstructed image qualities [10]. By measuring the spatial sensitivities of each voxel hence optimize the currents provided better results of reconstruction. This proved that by altering the simulation configurations, the results of reconstruction may differ as well. In other similar imaging techniques like magnetocardiography [11] and focal magnetic stimulation [12], the sensors position and the effects of coils were studied under different conditions. Thus, the studies on these parameters are very important in MNI in order to create the best results. In this thesis, the focus on the effects of coils are emphasized and studied with different configurations.

1.3 Objective

This thesis discusses the optimization of coil diameters in magnetic nanoparticles imaging. The application of magnetic nanoparticles is based on the magnetorelaxometry which the magnetic field is generated by the magnetic coils and highly influenced by the diameters of the coil. In order to provide the promising results, the diameter of the magnetic coil is one of the important parameters in image reconstruction. In this thesis, an optimization method based on particle swarm optimization has been introduced. The main objectives of the related works are:

- To investigate the effects of the excitation coils configuration on the reconstructed results.
- To examine the possibility of coils diameters optimization with particle swarm optimization method.

1.4 Scope

The studies in this thesis are focused on the measurement of magnetorelaxometry of magnetic nanoparticles and reconstruction images of the samples. The configurations of the excitation coils are studied by varying the number of coils, diameter of coils, arrangement of coils, shape of coils and the effects of the offset value of truncated singular value decomposition. The results are then compared with the correlation coefficient of the reconstruction with the computed data. Besides, in order to examine the possibility of optimization by using particle swarm optimization technique, the algorithm development is focused on the magnetic field calculation and the position vector determination.

1.5 Signification of Study

The outcomes of this study will contribute to justify the effects of varying the excitation coils' configurations in magnetic nanoparticles imaging. Other than that, the outcomes will help to create an optimum configuration to obtain the best result. The exposure of excessive of magnetic field to the human will be harmful to human. Hence, the study to obtain an optimum setup for magnetic nanoparticles imaging are very important in order to reduce the side effects of the device before applying on human.