HYBRID INERTIAL-MANIPULATOR BASED POSITION TRACKING SYSTEM FOR ULTRASOUND IMAGING APPLICATION

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Specially dedicated to

my mother, Rahmah for her motivation and blessing,

my lovely wife, Farah Awatif for her special support, love and understanding.

Thanks for always being there for me.

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ABSTRACT

In medical field, ultrasound imaging is one of the imaging modalities that needs position tracking system (PTS) in enlarging field of view (FoV) of an image. The enlarged FoV will result easier scanning procedure, and produce more accurate and comprehensive results. To overcome the weakness of commercially available PTSs which suffer from interference and occlusion, many researchers proposed improved PTSs. However, the improved PTSs focused on the portability and compact design, neglecting the vertical scanning aspect which is also important in ultrasound imaging. Hence, this research presents the development of hybrid inertial-manipulator based PTS for 3-dimensional (3D) ultrasound imaging system which capable of measuring the horizontal and vertical scanning movements. The proposed PTS uses the combination of inertial measurement unit sensor and manipulator. The research involves design and evaluation processes for the PTS. Once the design process of the PTS is completed, forward kinematics is calculated using Denavit-Hartenberg conversion. The next step is to evaluate the accuracy and repeatability of the output of the designed PTS by comparing with five sets of reference trajectory of ABB robot. A comparison of the accuracy for the proposed PTS with three other available PTSs is done using the horizontal movement's error. The experimental results showed high repeatability of position output reading of the designed PTS with standard deviation of 0.27 mm in all different movements and speeds. The proposed PTS is suitable to be used in ultrasound imaging as the error is less than 1.45 mm. Furthermore, the proposed PTS can measure the vertical scanning movement which is neglected in all the previous works, thus fulfilling the main objective of the research.

ABSTRAK

Dalam bidang perubatan, pengimejan ultrasound adalah salah satu modaliti pengimejan yang memerlukan sistem pengesan kedudukan (PTS) bagi membesarkan medan penglihatan (FoV) imej. FoV yang dibesarkan akan menyebabkan prosedur imbasan lebih mudah dan menghasilkan keputusan yang lebih tepat dan menyeluruh. Bagi mengatasi kelemahan PTS komersial yang mengalami masalah gangguan dan halangan penglihatan, ramai penyelidik yang mengusulkan PTS diperbaik. Namun, PTS diperbaik memfokuskan unsur mudah-alih dan reka bentuk kompak, mengabaikan aspek imbasan menegak yang merupakan aspek penting dalam pengimejan ultrasound. Oleh itu, kajian ini membentangkan pembangunan PTS berdasarkan gabungan *inertia-manipulator* untuk pengimejan ultrasound 3-dimensi (3D) yang mampu melakukan pergerakan imbasan mendatar dan menegak. Bagi mencapai matlamat ini, PTS perlu direka bentuk dan kemudian dinilai. Setelah proses reka bentuk PTS selesai, kinematik hadapan dikira menggunakan kaedah penukaran Denavit-Hartenberg. Langkah seterusnya adalah untuk menilai ketepatan dan keterulangan output kedudukan PTS dengan membandingkan lima set trajektori rujukan robot ABB. Perbandingan ketepatan PTS yang dicadangkan dengan tiga PTS sedia ada dilakukan menggunakan ralat pergerakan mendatar. Keputusan eksperimen menunjukkan keterulangan yang tinggi dengan sisihan piawai 0.27 mm dari bacaan output kedudukan PTS yand direka bentuk dalam semua pergerakan dan kelajuan yang berbeza. Secara keseluruhan, PTS yang dicadangkan adalah sesuai untuk digunakan dalam pengimejan ultrasound kerana ralat yang dicatatkan kurang daripada 1.45 mm. Selain itu, PTS yang dicadangkan mampu mengukur pergerakan pengimbasan menegak yang diabaikan dalam semua PTS sebelumnya, dan memenuhi objektif utama penyelidikan.

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LIST OF ABBREVIATIONS

ABS	-	Acrylonitrile Butadiene Styrene
AC	-	alternate current
CAD	-	computer-aided design
CCD	-	charge-coupled device
COTS	-	commercially off-the-shelf
DC	-	direct current
D-H	-	Denavit-Hartenberg
DMP	-	Digital Motion Processing
DOF	-	degree of freedom
DSP	-	digital signal processor
FAST	-	Features from Accelerated Segment Test
FoV	-	field of view
IBVS	-	image-based visual servoing
IMU	-	inertial measurement unit
INS	-	inertial navigation system
IR	-	infrared
LED	-	light-emitting diode
LOS	-	line-of-sight
MEMS	-	microelectromechanical
PBVS	-	position/pose-based visual servoing
PPR	-	pulse per revolution
PTS	-	position tracking system
SCARA	-	selective compliance assembly robot arm
SIFT	-	Scale-Invariant Feature Transform
SURF	-	Speed-Up Robust Feature

LIST OF SYMBOLS

C	-	encoder count value
X	-	number of encoder’s pulse
r	-	radius of encoder’s shaft in radian
θ_i	-	joint *i* angle
α_i	-	link *i* twist
d_i	-	link *i* offset
a_i	-	link *i* length
a_1	-	first link length
a_2	-	second link length
d_3	-	third link offset
d_6	-	sixth link offset
T_i	-	homogeneous transformation matrix
${}^{0}_{6}T$	-	forward kinematics for end effector as refer to base frame
${}^{0}_{1}T$	-	homogeneous transformation matrix for Joint 1
${}^{1}_{2}T$	-	homogeneous transformation matrix for Joint 2
${}^{2}_{3}T$	-	homogeneous transformation matrix for Joint 3
${}^{3}_{4}T$	-	homogeneous transformation matrix for Joint 4
${}^{4}_{5}T$	-	homogeneous transformation matrix for Joint 5
${}^{5}_{6}T$	-	homogeneous transformation matrix for Joint 6
X_{POSE}	-	X coordinate position of end effector
Y_{POSE}	-	Y coordinate position of end effector
Z_{POSE}	-	Z coordinate position of end effector
G_x	-	gravitational acceleration on X-axis
G_y	-	gravitational acceleration on Y-axis
G_z	-	gravitational acceleration on Z-axis

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Position tracking system (PTS) has been greatly developed for decades[1–7]. Its uses have confirmed enormous advantages in many fields, either stand alone for its own tracking purposes or for supporting other devices in data localization. By definition, the objective of a PTS is generally intended for object observation in term of location and movement recorded in an extent of time by measuring position and orientation in both virtual and real worlds, characterized by data acquisition, precision, working range and degree-of-freedom (DOF), and depending on the nature of the system and applications. With the capability in localizing specific position and identifying motion of an object, PTS has played a big role in many important applications, such as aeronautics and transport system [8, 9], military[10, 11], telecommunication[12, 13], remote sensing[14], robotics and mechanical engineering[15, 16], biology and medicine[17, 18], and sports and entertainment[19, 20].

Along with the vast development of sensors[21, 22] and computational system[23, 24], and with its high market demand in many applications, the PTS's technology progression is nowadays growing tremendously. Various new PTSs have been released to the market triggering a great growth of new devices supported by PTSs. However, due to the need of technology suitability study with its application, not all PTSs can be directly applied. Defining the best technology must be confirmed by specifying the application details and the PTS's technology based on standards[25], characteristics and purposes[26], and environment[27]. Sensor characteristics, such as type, accuracy, robustness, latency, and applicability, need to be concurrently considered in determining a suitable PTS and matching them for certain purpose.

PTS have also been commonly used in biology and medical fields, ranging from tracking human motion to assisting invasive procedure in combination with surgical instruments. In biology, the applications are mostly for supporting cellular imaging technology for miniscule object observation[17]. While in the medical field, the applications are much wider, including diagnostics [28, 29], image-guided navigation system for therapeutic, intervention and surgical assistance [30–32], and rehabilitation medicine [33–35].

Comparing to other imaging systems, ultrasound imaging is one of the imaging modalities which highly implements PTSs for its clinical applications, both non-invasively and invasively. The uses of ultrasound imaging are highly encouraging because of its non-radiation exposure, real-time, low-cost, high mobility, and ease of application in scores of clinical environments. Still, in spite of its handy size, ultrasound probe has some limitations in conducting diagnosis and treatments. The freehand uniqueness of the ultrasound probe enables the operator to sweep the ultrasound probe and grab the image based on the surface contour of the body and direct it to specific region of interest for thorough investigation. Consequently, freehand ultrasound imaging process is highly depending to skill of operator. Unlike skilled operators who can easily find the exact position of the object of interests, unskilled ones need to understand the anatomical structure of the scanned location and sweep much longer to reach the exact location and obtain the correct image. Such work is often time consuming and has higher error risks that may affect the diagnosis or treatment results[36–38].

Besides freehand complication, the narrow field of view of the ultrasound probe also causes difficulties in image visualization and interpretation as well as object localization. Such difficulties may also hamper accuracy in performing diagnosis and treatment. Additionally, these problems become more complicated in treatment monitoring when the ultrasound imaging is used in common with other imaging modalities with different characteristics, such as MRI, CT, and so on.

Therefore, an extended view technique is used to enlarge the field of view[39, 40]. With the advancement of PTSs and their possibilities to integrate with the ultrasound imaging system, field of view enlargement can be performed, resulting in an easier scanning procedure, with more accurate and comprehensive results. This progression has brought the ultrasound imaging system to become more accurate, interactive, multidimensional, and ubiquitous with other systems.

As mentioned above, there are varieties of position tracking technologies developed until now, but not all of the PTSs can simply be used in ultrasound imaging. This is due to the limitation, advantages and disadvantages of each PTS which limits the compatibility with ultrasound imaging devices. The main objective of this research is to develop PTS for ultrasound imaging, specifically for 3D ultrasound imaging. Due to their disadvantages, the PTS will use neither of the currently available PTSs which are optical tracking system and electromagnetic tracking system. Instead, this research proposed a combination of inertial measurement unit (IMU) and manipulator as the PTS.

1.2 Problem Statement

There are two types of commercially available PTSs used to track the probe position for ultrasound imaging which are optical tracking system and electromagnetic tracking system[41, 42]. However, both PTSs suffers from some disadvantages such as occlusion problem [43] and distortion of magnetic field [43, 44]. Due to these disadvantages, other PTSs that have been proposed by other researchers for the same motive. The proposed PTSs will be reviewed and their advantages and disadvantages will be highlighted in the next chapter. But, overall, all of the proposed PTSs focused on the portability and compact design which then limits their usage of the PTSs for only horizontal movements. In other words, the proposed PTSs for ultrasound imaging doesn't measure the vertical movements. The vertical movements are useful for ultrasound imaging especially for spine scanning or pregnancy scanning and it will be discussed further detail in Chapter 2. Therefore, a PTS for ultrasound imaging which also cover the vertical movement scanning is needed.

1.3 Research Objectives

The main objective of this research is to develop a PTS for 3-dimension (3D) ultrasound imaging system which capable of measuring the horizontal and vertical scanning movements. In order to achieve the main objective, several sub-objectives are highlighted below.

The sub-objectives of the research are:

I. To design and fabricate manipulator for the ultrasound probe attachment and PTS.
II. To calculate the position of ultrasound probe using forward kinematics equation with Denavit-Hartenberg (DH) convention.
III. To do experimental analysis of the fabricated PTS, using reference trajectory of ABB Robot.

1.4 Scope of Work

The followings are the scopes of the research:

I. The design and fabrication of the manipulator will focus on the proof of concept to be used in ultrasound imaging environment.
II. Experimental analysis are done in several motion paths based on the basic movements of the ultrasound scanning techniques.

1.5 Thesis Outline

This thesis is organized as follows. There are 5 chapters in total. Chapter 1 provides a brief introduction of PTS in general and then narrowed down to the PTS used in medical fields. The objectives and the problem statement of the research were also stated in this chapter. The scopes of works for this research were explained at the end of the chapter.

Chapter 2 presents the literature review of the related works regarding the research topic. It starts with a discussion on the previous literature regarding PTS and ultrasound imaging. Types of the indoor PTS which is the focus of this research were presented in detail. Next, the ultrasound imaging system is presented by highlighting the needs for PTS in the field. At the end of the chapter, PTS for ultrasound imaging developed by previous researchers were discussed by taking into account their advantages and disadvantages.

In Chapter 3, the step by step methodology approaches used throughout the research is presented. The approaches were done in order to achieve the objectives highlighted in Chapter 1. This covers the design of PTS, forward kinematic calculation, and lastly fabrication and experimentation. MATLAB software, Solidworks software, ABB Robot have all been used for simulations, evaluations and experimentations. Each part of the methodology was discussed in details in the chapter.

Chapter 4 presents the results of all the simulations, evaluations and experimentations done in this research. This chapter covers the results of experimental works done using ABB Robot to evaluate the accuracy and consistency of the PTS. All the results were presented, discussed and summarized in this chapter.

Chapter 5 summarized the findings of this research, thus recommending the future work that can be done to improve the research project.

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