KINEMATIC DESIGN AND ANALYSIS OF A 2RPS-1PRS PARALLEL MANIPULATOR FOR HOSPITAL BED REPOSITIONING SYSTEM

by

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LIST OF ABBREVIATIONS

HBRS	Hospital Bed Repositioning System
DH	Denavit & Hartenberg
RPS	Revolute-Prismatic-Spherical
PRS	Prismatic- Revolute-Spherical
DoF	degrees of freedom
CAD	Computer-Aided Design
VDC	Voltage Direct Current
DC motor	Direct current motor
LCD	Liquid Crystal Display
3D	Three Dimensional
POSE	Position and Orientation

LIST OF SYMBOLS

A_i	Position of limbs in bottom platform (i =1, 2, 3)
B_i	Position of limbs in top platform (i =1, 2, 3)
D_i	Position of revolute joints in mechanism (i =1, 2, 3)
k_i	Length of linear actuator (i =1,2,3)
q	Length of linear actuator
L_i	Length of side i for equilateral of bottom platform $A_1A_2A_3$ (i =1,2,3)
l_i	Length of side i for equilateral of top platform $B_1B_2B_3$ (i =1,2,3)
θ	Rotation angle of moving frame O about the v-axis
ψ	Rotation angle of moving frame O about the u-axis
a	Radius of bottomplatform
b	Radius of top platform.
X_o, Y_o, Z_o	The centre point coordinate of fixed frame, O
$\theta_{2,1}$	The rotational angle of the x_1,1 axis about the z_1,1 axis, such that current x_1,1 axis will be parallel to the x_2,1 axis after rotation
ϕ	An offset angles of fixed base platform
λ	An offset angles of moving base platform
r	Radius of frames
l	Length of frames
O	Center point at top platform
o	Center point at bottom platform
a_i	Link length
α_i	Link twist angle
θ_i	Joint angle
d_i	Joint distance
k_n	The distance from the origin of the frame $x_{1,n}, y_{1,n}, z_{1,n}$ to the origin of the frame $x_{2,n}, y_{2,n}, z_{2,n}$.
$T_{1,n}^{0,n}$	The transformation matrices of limb i (i = 1, 2, 3)
$T_{2,n}^{1,n}$	The transformation matrices of limb i (i = 1, 2, 3)

Reka Bentuk dan Analisis Kinematik Sebuah Pengolah Selari 2RPS-1PRS untuk Sistem Kedudukan Semula Katil Hospital

ABSTRAK

Sistem kedudukan semula katil hospital (HBRS) telah menjadi salah satu kajian terpenting untuk mengurangkan kecederaan fizikal dalam kalangan penjaga semasa aktiviti pengendalian pesakit. Walau bagaimanapun, ciri-ciri katil hospital seperti ketinggian yang boleh disesuaikan, peningkatan, kedudukan semula secara lateral, dan pusingan sebagai ciri-ciri mekanisme kendiri secara amnya tidak berkesan kerana kekerapan penjaga perlu mengubah katil bagi mencapai kedudukan diingin. Kekerapan pengulangan ini boleh meningkatkan risiko kecederaan fizikal akibat tekanan di kalangan penjaga. Dari segi reka bentuk berstruktur untuk HBRS, konfigurasi pengolah selari boleh menjadi pendekatan yang berkesan untuk mengintegrasikan ciri-ciri tersebut ke dalam satu reka bentuk katil hospital. Walau bagaimanapun, penggunaan pengolah selari sebagai reka bentuk berstruktur yang mampu mengintegrasikan ciri-ciri katil hospital merupakan suatu masalah yang mencabar akibat keterbatasan ruang kerja. Oleh itu, objektif-objektif kajian ini adalah untuk membangunkan model kinematik dan untuk menganalisis prestasi pengolah selari dalam sistem HBRS dengan mempertimbangkan ciri-ciri Trendelenburg, anti-Trendelenburg, mengubah kedudukan, dan ketinggian yang boleh disesuaikan. Reka bentuk dan pembangunan model kinematik berasaskan Denavit & Hartenberg untuk mekanisme selari yang dicadangkan iaitu 2RPS (sambungan revolut-sambungan prismatik- sambungan sfera)-1PRS (sambungan prismatik- sambungan revolut- sambungan sfera) diperlukan untuk meneliti keperluan fungsi mekanisme HBRS. Berasaskan model kinematik ini, ruang kerja dan kesingularan pengolah selari 2RPS-1PRS yang dicadangkan telah dianalisis untuk menentukan tingkah laku mekanisme tersebut. Kemudian, simulasi berangka telah direka bentuk menggunakan perisian MATLAB dan prototaip perkakasan mekanisme ini telah digunakan untuk mengesahkan prestasi pengolah selari 2RPS-1PRS yang dicadangkan. Berdasarkan geometri tertentu, keputusan simulasi dan keputusan eksperimen dengan ralat pemasangan dan julat sudut sfera telah menunjukkan trend yang sama dalam had kesalahan 5% untuk sendi aktif dan pasif, Penemuan ini menyerlahkan keupayaan ciri-ciri bersepadu dalam HBRS berasaskan mekanisme pengolah selari 2RPS-1PRS berfungsi lebih baik daripada ciri-ciri kendiri. Integrasi ciri-ciri HBRS dengan pengolah selari 2RPS-1PRS menawarkan satu mekanisme mudah yang boleh memberikan pelbagai pergerakan, seperti menggulingkan, mencondongkan, dan mengalihkan yang mewakili pergerakan berfungsi katil hospital yang sedia ada.

Kinematic Design and Analysis of a 2RPS-1PRS Parallel Manipulator for Hospital Bed Repositioning System

ABSTRACT

Hospital Bed Repositioning System (HBRS) has become one of the most important studies to reduce physical injuries among caregivers during patient handling activities. However, hospital bed features, such as adjustable height, boosting, laterally repositioning and turning based on standalone mechanisms are generally ineffective since caregiver needs to frequently adjust the bed to get into the desired position. These frequent repetitions may increase the risk of physical injury of stress among caregiver. In terms of the structured design for the HBRS, the configuration of a parallel manipulator could be an effective approach to integrate these features into one hospital bed design. However, employing the parallel manipulator as a structured design with the ability to integrate specific features into a hospital bed can be a challenging issue due to the limitation of workspace. Hence, the objectives of this study were to develop a kinematics model and to analyse the performance of a parallel manipulator in the HBRS by considering the Trendelenburg, anti-Trendelenburg, repositioning, and height adjustable features. The design and development of the kinematics model based on the Denavit & Hartenberg method for the proposed parallel mechanism of 2RPS (revolute joint-prismatic joint-spherical joint)-1PRS (prismatic joint-revolute joint-spherical joint) was required to examine the functional requirements of the HBRS mechanism. Based on this kinematics model, workspaces and the singularity of the proposed 2RPS-1PRS parallel manipulator were analysed to determine the behaviour of the mechanism. Then, a numerical simulation that was designed using the MATLAB software and the prototype of the hardware mechanism were used to verify the performance of the proposed 2RPS-1PRS parallel manipulator. On specific geometry, the simulation and experimental results, considering the limitations of assembly errors and range of spherical angles, showed a similar trend within 5% error for active and passive joints. This finding highlighted the capability of the integrated features in the HBRS based on the mechanism of the 2RPS-1PRS parallel manipulator, which performed better than the standalone features. The integration of the HBRS features with the novelty of 2RPS-1PRS parallel manipulator offered a simple mechanism that could provide various motions, such as rolling, tilting, and shifting that represent the functional motions of existing hospital beds.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

This chapter will provide an overview of the study and the structure of this thesis. This chapter will introduce the background of the study, followed by the problem statement and research objectives. The scope of this research and the significance of its findings are also discussed in this chapter

1.2 Research Background

Hospital Bed Repositioning System (HBRS) has received more attention from industrial manipulator manufacturers and concerned researchers in the last several decades. This is due to the potential application of the HBRS to provide specific features in hospital beds that can assist caregivers with common patient handling activities. These features can reduce physical injuries or musculoskeletal disorders among caregivers. However, according to Zhou & Wiggermann (2021) hospital bed features, such as boosting, lateral repositioning, and turning patients based on the HBRS will only be more effective to caregivers when they are integrated in a single hospital bed rather than being standalone features. Thus, kinematics design and analysis of the HBRS is a challenging issue that must be addressed, since the integration of different features in a hospital bed is essential.

Additionally, kinematics design and analysis of the HBRS in single design is necessarily needed because able to reduces the pressure injuries among caregivers during performing reposition task. According to Wiggermann (2016), the source of injuries such back and shoulder pain, often result from the task of turning patients that requires lower physical demand when patients needed to changing lines, bathing, inspection for wounds, changing wound dressings, placing bedpans and repositioning to prevent bedsores. The author also highlighted the solution of these injuries, many manufacturing provided the turn assist features in the hospital bed mattresses. These features provided one or more air bladders in order to inflate to partially rotate the patients. However, the turn assist features is not being use among caregivers due its not a standard safe patient handling care practice.

In the effort to address the kinematics design of the HBRS to integrate different features, various types of mechanism designs have been proposed. As reported by Wiggermann et al. (2019), the Hillrom Centrella® Smart+ hospital bed consists of several features, such as turn assist, Trendelenburg, and mattress maximum inflation. The mechanism for the turn-assist feature uses air bladders to tilt the patient laterally on the bed to a maximum 30° from the horizontal position when one side of the mattress is inflated, as shown in Figure 1.1 (Zhou & Wiggermann (2021)). The turn assist feature utilises a different mechanism than the Trendelenburg feature. Due to the complex structure of the HBRS design, standalone features are normally selected for study, but this may cause the dynamic properties related to the repositioning mechanism to be lost. Thus, the parallel mechanism was proposed in this study to offer a realistic option for the structural design of the HBRS.

Figure 1.1 The activity of turning process in HBRS

Parallel mechanisms as the structural design of the HBRS could offer more advantages in terms of fewer actuator applications, simple structures, and low costs. Numerous researchers have studied parallel mechanism in kinematics designs and analyses in order to determine the behaviour of each mechanism that can meet specific requirements. According to Zhang & Zhang (2013), the parallel mechanism consists of a top moving platform, a fixed base platform, three revolute joints, three spherical joints, and three linear legs. Combinations of these links and joints give this parallel mechanism the ability to perform pitches, rolls, and vibrations in vehicle driving simulators. To make the application of the HBRS demonstrate the distinct effect of motions related to this parallel mechanism, the mechanism proposed by Zhang & Zhang (2013) was modified to meet the requirements of the features in the HBRS. However, to realise this proposed parallel mechanism as the structural design of the HBRS to fulfil the integration features, a suitable kinematics design must be considered to synthesise the machine elements, such as a top moving platform, a bottom platform, and active and passive joints that can perform the motions of the previously mentioned integrated features.

In order to comprehend the pose of the proposed parallel mechanism that can fulfil the motions of the integrated features in the HBRS, kinematics designs based on several calculation methods have been proposed for developing a kinematics model. The most logical approach was by involving the Denavit & Hartenberg (DH) method to design the kinematics model for the proposed parallel mechanism. Based on this kinematics model, the position and orientation (pose) of the top moving platform can be predicted without placing force on it. As reported by Dumlu & Erenturk (2013), the kinematics model of a 6-DOF parallel manipulator was successfully formulated using the DH method by considering the interactions between the input links and the coupler links of the manipulator. They also found that the simulation results of the manipulator model showed that its mechanisms have the ability to improve the quality of the trajectory tracking control of the parallel manipulator. In this study, the intangible mechanisms of the kinematics model based on the DH method were determined using the kinematics simulation approach. The simulation results were then used to develop and analyse the behaviour of the top moving platform, which would be able to perform the motions of the integrated features in the HBRS.

According to Masood, M. U., & Haghshenas-Jaryani (2021), kinematics simulations based on a kinematics model for a robot to be used for harvesting Chile peppers were used to generate, verify, and simulate the robot’s motions to achieve the pose of the desired end-effectors. The algorithm of this simulation programme that was developed using the MATLAB software was based on mimicking the behaviours of real-world systems. This simulation programme also consisted of joint angles, while the end-effector for a specific object's pose was represented in the 3D Cartesian space. Based on the idea of this kinematics simulation, a kinematics model was developed in this study. The aim was to represent the proposed parallel manipulator that can fulfil the motions of the integrated features in the HBRS. Additionally, since the proposed parallel mechanism has a significant degree of structural freedom, the performance of the kinematics model was examined in order to understand the behaviour of the proposed parallel manipulator in the HBRS.

Kinematics performances, such as in workspaces and singularity represent the process that is involved in designing mechanisms in order to analyse the characteristics of parallel manipulator. Yang et al. (2018) reported that the kinematics performance obtained from the derivation of a kinematics model for the parallel manipulator was good in terms of workspace. The stiffness of the parallel manipulator has also satisfied their requirements and no singularity position happened within the workspace. Based on their results, kinematics performance might be able to indicate the performance of the proposed parallel manipulator.

Several studies have explored the current mechanism rehabilitation features for hospital bed repositioning systems. Andhare & Onkar. (2021) developed mechanism of bed with features such as commode parts, side turning and transform bed function from sleeping position. W. Li & Lu. (2020) proposed mechanism that able to turn the angle with less than 80°of a patient's body to the left and right at bed platform. Seon et al.

(2021) studied the multiple segments using brushless motor and fuzzy controller controls to control body pressure among bedridden patients. Meanwhile, Hiray & Kulkarni. (2020) designed automatic position-adjusting beds with cover the function such as blood circulation, back pain, and musculoskeletal disorders among patients. Tian, Wang, Zhang, Su, Wang, et al. (2021) studied the transfer assist system devices on the top platform of the hospital bed reduced the pressure among caregivers. However, these studies of collectively have highlight the features of HBRS such as lateral repositioning, Trendelenburg, anti-Trendelenburg, and adjustable height into a single design are still lacking.

Therefore, the kinematics design and analysis of the proposed parallel manipulator were important parts of the design decision that arose when designing the HBRS system to meet the requirements of integrated features and to provide a simple mechanism. Based on the current kinematics design and analysis used in the HBRS system, the integration of features in a single design would increase the complexity of the mechanisms, which would lead to the analysis of standalone features only. Based on this limitation of the HBRS system, the parallel mechanism was selected as the structural design that could meet this requirement. The kinematics design of the proposed parallel manipulator was developed to study the ability of the top moving platform to perform the motions of integrated features. Kinematics simulation was performed to ensure that the model was concrete. Finally, kinematics analysis was conducted on the proposed parallel manipulator based on workspaces and singularity by identifying the characteristics of its mechanisms. Consequently, the proposed parallel manipulator, as a structural design in the HBRS, would be able to perform the motions of the integrated features.

1.3 Problem Statement

Kinematics design and analysis is an important part of a design process for developing the HBRS that can meet the requirements of caregivers and patients while performing repositioning tasks. Kinematics design and analysis were conducted in this study to create simple structural mechanisms that can integrate the features of the HBRS into a single design. The structural mechanism was built from a combination of machine elements, such as linkages, joints, and actuators for produces with specific motions based on the functions of the HBRS. Close attention on the design process in the development of the HBRS helped to create an innovative mechanism that can fulfil the requirements of caregivers and patients.

However, breakthroughs in the design process of multi-functional HBRS are still lacking. This is due to the complex structures of the mechanisms for the HBRS when the multi-functions of hospital beds are integrated into one design. Consequently, the standalone features of the HBRS are getting more attention from researchers and used the most by caregivers in hospitals, because they are easier to obtain compared to beds with integrated features. This scenario would expose the caregivers to physical stresses and uncomfortable working conditions during patient repositioning tasks. This scenario could also increase the risk of developing bedsores among patients when they lay in bed for longer periods. Unsuitable kinematics design and analysis of the HBRS could lead to the ineffective use of hospital bed features among caregivers and patients.

Therefore, the aim of the study was to conduct kinematics design and analysis of the HBRS and to produce a simple design structure of the mechanism that can integrate the different features of the HBRS into a single design. The design structure of the HBRS in this study incorporated the proposed 2RPS-1PRS parallel manipulator, which was able to perform three degrees of freedom, roll attitude, pitch attitude and z axis translation, which realizes the features of HBRS, such as the laterally repositioning, Trendelenburg and anti-Trendelenburg, and adjustable height, respectively. Then, to understand the behaviour of the proposed 2RPS-1PRS parallel manipulator, kinematics analysis was performed on the motions of the existing system without placing any forces on it. The structure of the HBRS was also verified to ensure that the model and its hardware can meet the requirements of integrated features.

1.4 Objectives of the Study

The objectives of this study were as follows:

a) To develop a kinematics design of the proposed 2RPS-1PRS parallel manipulator that can perform different functions in HBRS, such as Trendelenburg, the anti-Trendelenburg, repositioning, and adjustable height.

b) To perform kinematics analysis of the proposed 2RPS-1PRS parallel manipulator that would be applied into the HBRS, in term of workspaces and singularity.

c) To validate the efficacy of the kinematics model using a prototype of the proposed 2RPS-1PRS parallel manipulator.