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A ROBOTIC MANIPULATOR TRAJECTORY MONITORING SYSTEM IN VIRTUAL ENVIRONMENT

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A ROBOTIC MANIPULATOR TRAJECTORY MONITORING SYSTEM IN VIRTUAL ENVIRONMENT

By

HUDA HATAM DALEF

This Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2018

DEDICATION

To my Parents,

my lovely Husband, Muhammed Delaf,

my daughter: Mays,

my sons: Abdul Muhaiman and Abdul Wadod

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

A ROBOTIC MANIPULATOR TRAJECTORY MONITORING SYSTEM IN VIRTUAL ENVIRONMENT

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December 2018

Chairman : Associate Professor Faieza Abdul Aziz, PhD
Faculty : Engineering

The user interface or commonly known as human–computer interaction (HCI) has become the focus of most researches as the usage of computers increases in nearly all manufacturing machines. The design parameters of HCI include hardware and software related parameters. Virtual Environment (VE) can be employed to interpret these interactions; however it is challenging to integrate VE-assisted simulation tools because the hazard of touching the machine and the difficulty of monitoring are among the most prominent problems in intelligent industries. Many accidents have been associated with robot manipulator operations, where the total number of fatalities in the United States was 4,585 and over 1,300 workers were injured in 2013, because of hardware and software complexity or the insufficient knowledge and skills of technicians in operating and monitoring the equipment. The accurate control of motion axes is a fundamental concern in intelligent industries, in which an exact end-effector trajectory is required at the correct time. It is also essential for efficient system operation and to predict the position and time error of the trajectory. Therefore, there is a need for a solution that can provide convenient and intuitive robot manipulator control with user's location independence, easy adjustment and simultaneous monitoring of robot manipulator motion tasks. The main objective of this research is to develop a robotic manipulator trajectory monitoring system in VE. Therefore, the first objective is to enhance monitoring trajectory system of robot manipulator using wireless control system. Additionally, to describe the trajectory a mathematical model and parameter optimization based on VE data was derived. This work adopts a robot manipulator as a scale down of the actual industrial machine. The Zigbee-based wireless communication system consists of only a pair of XBee S1 Pro. MATLAB graphical user interface GUI-based environment involving the 3-D animation of the actual structure is presented to demonstrate real-time moving of the end-effector trajectory. An integrated VE control and monitoring trajectory (VECMT) was built by matching the digital information with the user's environment, and a mathematical model was derived for the 3D structural mechanism to verify the VECMT system. In order to model the system hardware which was used to predict robot manipulator trajectory and enhance the overall monitoring system, Nonlinear Least Squares method was used as a measurement-based parameter optimization procedure. Therefore, this work presents several novel contributions to improve the trajectory state robot manipulator in VE. Firstly, the main achievement of this work is low power consumption for a wireless data network for 3D position monitoring, the proposed approach is efficient in terms of user cost level contribution because it adopts the concept of signal matching in the software configuration of components and a suitable selection of components dispenses of additional microcontrollers which ultimately achieves economic cost reduction. Secondly, the user perceives an integrated computer-based work environment and allows the user to easily merge the real world with a computer based environment in a high accuracy of 98.53% for elbow's joint and 97.5% for the base's joint. The estimation of the parameter simulation has been verified by comparing the target data with response data that shows a very good convergence (97.87% for elbow and 98.69% for base).

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SISTEM KAWALAN ROBOT MANIPULATOR DAN PENGAWASAR TRAJEKTORI PERSEKITARAN VIRTUAL

Oleh

HUDA HATAM DALEF

Disember 2018

Pengerusi : Profesor Madya Faieza Abdul Aziz, PhD
Fakulti : Kejuruteraan

Antaramuka pengguna yang sering dikenali sebagai interaksi di antara manusia dan komputer atau human computer interaction (HCI), telah menjadi tumpuan penyelidikan seiring dengan kenaikan penggunaan dalam hampir kesemua mesin pembuatan. Parameter rekabentuk HCI termasuklah parameter perkakasan dan perisian yang berkaitan. Persekitaran maya (VE) boleh digunakan untuk mentafsir kesemua interaksi ini, walaubagaimanapun ianya agak mencabar untuk menyatukan alat simulasi bantuan VE kerana bahaya akibat tersentuh mesin dan kesukaran pemantauan adalah antara masalah utama dalam industri pintar. Banyak kemalangan telah dikaitkan dengan operasi robot manipulator, di mana jumlah kematian di Amerika Syarikat direkodkan sebanyak 4,585, dan lebih 1,300 pekerja cedera pada tahun 2013 akibat kerumitan dan kekurangan pengetahuan dalam pengendalian dan pengawasan perkakasan dan perisian. Kawalan paksi gerakan yang tepat adalah kebimbangan asas dalam industri pintar, di mana trajektori efektor akhir yang tepat diperlukan pada masa yang betul. Ia juga amat penting bagi sistem untuk beroperasi secara lancar dan untuk menganggar kedudukan dan ralat masa trajektori. Oleh yang demikian, penyelesaian diperlukan bagi mewujudkan kawalan manipulator robot yang mudah dan bersifat intuitif berhubung kedudukan bebas pengguna, kemudahan ubahsuai dan pemantauan berterusan bagi aktiviti manipulator robot. Objektif utama kajian ini adalah untuk membentuk kawalan manipulator robot masa sebenar dan pemantauan sistem trajektori bagi aplikasi VE. Oleh itu, objektif pertama adalah untuk meningkatkan sistem trajektori pemantauan manipulator robot menggunakan sistem kawalan tanpa wayar. Sehubungan itu, bagi menerangkan trajektori, sebuah model matematik dan pengoptimum parameter berdasarkan VE telah dirumuskan. Penyelidikan ini menggunakan manipulator robot berskala rendah daripada saiz sebenar mesin industri. Sistem komunikasi tanpa wayar Zigbee terdiri daripada hanya sepasang Xbee S1 Pro. Persekitaran berasakan MATLAB GUI melibatkan animasi 3D dari struktur yang sebenar dibentangkan untuk menunjukkan pergerakan masa sebenar bagi kesan trajektori akhir. Seterusnya, VECMT bersepadu telah dibina dengan memadankan maklumat digital dengan persekitaran pengguna, dan model matematik dirumuskan untuk mekanisma struktur 3D bagi mengesahkan sistem VECMT. Dalam menghasilkan model sistem perkakasan yang digunakan untuk meramalkan trajektori manipulator robot dan meningkatkan keseluruhan sistem pemantauan, kaedah Nonlinear Least Square digunakan sebagai ukuran asas dalam langkah pengoptimuman parameter. Oleh itu, kajian ini membentangkan beberapa sumbangan baru bagi membaikpulih keadaan trajektori manipulator robot dalam VE. Pertama, pencapaian utama kajian ini adalah penggunaan tenaga yang rendah bagi rangkaian data tanpa wayar untuk pemantauan kedudukan 3D, cadangan ini adalah berkesan dalam sumbangan peringkat kos pengguna kerana ianya menggunakan konsep pemadanan isyarat dalam komponen konfigurasi perisian dan pemilihan komponen yang bersesuaian daripada kawalan mikro tambahan yang dapat mengurangkan kos secara ekonomik. Kedua, pengguna melihat persekitaran kerja berasaskan komputer bersepadu dan membolehkan pengguna untuk menggabungkan dunia sebenar dengan persekitaran berasaskan komputer dalam ketepatan yang tinggi iaitu 98.5% untuk sambungan siku dan 97.5% untuk sambungan pangkalan. Anggaran bagi pengoptimuman parameter telah disahkan dengan membuat perbandingan di antara data sasaran dengan data SMMJ yang menunjukkan penumpuan yang sangat baik (97.87% bagi siku dan 98.69% bagi pangkalan).

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I certify that a Thesis Examination Committee has met on 21 December 2018 to conduct the final examination of Huda Hatam Dalef on her thesis entitled "A Robotic Manipulator Trajectory Monitoring System in Virtual Environment" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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Declaration by graduate student

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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Name of Member of Supervisory Committee: Professor, Ir Dr. Mohd Khairol Anuar Mohd Ariffin

Signature: ______________________

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ADC	Analogue to Digital converter
AR	Augmented Reality
δ_t^j	the reading from channel j of the analog-to-digital converter at time interval t
CAD	computer-aided design
CAM	computer-aided manufacturing
CBM	condition-based maintenance, a synonym for predictive maintenance
CM	condition monitoring
CNC	Computer numerical control
DOF	Degrees of Freedom
DWCS	Development Wireless Controller System
EMF	electromotive force
HCI	human–computer interaction
GUI	Graphical User Interface
GUICMT	Graphical User Interface of Control and Monitoring Trajectroy
Kv	voltage scale down constant
Ki	The current scale down constant
L-E	Lagrange-Euler formulation
I	Current
IRLS	iteratively reweighted least square
RF	Radio frequency
RMS	Root mean square
RPM	revolutions/minute
MME	machine modelling environment

N-E	Newton-Euler formulation
OLS	ordinary least squares
PWM	pulse width modulator
QS	Queried Sampling
SCAMS	Supervisory Control and Monitor System
SMDCS	Simulation Model of DC servomotor
SMEs	small and medium sized enterprises
SMMJ	Simulation Model of Robot manipulator's Joint
SPIF	Single Point Incremental Forming
STC	Self-Tuning Controller
T_d	Day time over which the integration applied
V	Voltage
VE	Virtual Environment
WiFi	Wireless Fidelity
VEAM	Virtual Environment Aided Manufacturing
VECMT	Virtual Environment of Control and Monitoring Trajectory
VEs	Virtual Environments
Vout	The scale down output voltage
VR	Virtual Reality
VRML	Virtual Reality Modelling Language
VM	Virtual Manufacturing
WLS	weighted least square
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Research Background

The technological developments in the field of intelligent machines and their applications in various industries have been growing rapidly, and therefore, have become an interesting subject to explore. Nevertheless, an important concern remains on how to make an intelligent machine functions properly and follows orders from the controller directly or through a computer. Virtual environments (VEs) provide safe and cost-effective environments for learning and 'hands-on' training. Recent initiatives in computers and graphics card speed are making VEs increasingly more realistic (i.e. closer to physical environments), particularly from the visual and auditory perspectives. Accordingly, VEs are becoming increasingly attractive in education and training applications (Gogouvitis et al., 2015; Gupta et al., 2008). Interactive 3D VEs provide enabling circumstances for innovation and evolution in the education system, training, maintenance and repair operations of industrial plants. In fact, techniques such as complete 3D simulation of production processes and manufacturing facilities, promote a new approach for technical documentation and assistance where the user can be easily guided through even the most complex and critical operations (El-Chaar et al., 2011).

Commonly, several errors encountered in manufacturing process are problems related to robot manipulator's trajectory. The accurate control of motion axes is a fundamental concern in intelligent industries, in which an exact trajectory is required at the correct time in order to predict the position and time errors of the trajectory. Some of these errors can be reduced by monitoring and controlling the process and environmental parameters of devices (Caricato et al., 2014). Control and automation with feedback are possible through dedicated control using computers because most of the industrial machines have become advanced tools. The computer allows the full or partial automation of different or complex procedures with increased security and precision. Real-time data processing is attainable, and many parameters (e.g. orientation, speed and acceleration) can be controlled through the computer interface (Sun et al., 2001). In addition, a manipulation task is typically given in terms of the desired end-effector trajectory. Robot manipulator is controlled by joint servos; thus, the task space should be mapped to the joint space. Trajectory planning converts the description of a desired motion into a trajectory, thereby defining the time sequence of the intermediate configurations of the robot manipulator between the origin and the destination (Gaschler et al., 2014).

1.1.1 Industrial Machines

Industrial machines have become advanced tools where automation and advanced feedback is made possible through dedicated control computers. The computers allow us to fully or partially automate complex procedures and can help to make manual control more secure and precise. There are different industrial machines to implement various tasks of manufacturing processes that are specific in the production line, such as arc welding, assembly, polishing, spray painting, milling, pick and place, cutting and drilling (Al-Ghamdi et al., 2015; Davarpanah et al., 2015). Normally, manufacturing process are performed using three-axis computer numerically controlled (CNC) machine or Roboforming, such as the robot manipulator-type EDARM ED-7100. The robot manipulator mechanism consists of the physical construction of the body, arm and wrist on the machine. The body lies on a base, the arm is attached to the body and the wrist section is situated at the end of the arm. The relative movement between the various components of the body, arm and wrist is possible with the series of joints or gears. The robot manipulator can perform rotational and sliding movements. While, the structure of parts can be constructed to achieve the needed point from collectible of grouped movement of the joints which is called robot manipulator wrist or the end effector. The end effector is not included in the joint mechanism, the body of the robot manipulator is used to adjust the position or location of the end effector and the wrist joint is used to set the direction towards (orientation) of the end effector (Corke, 1995; Khalil et al., 2007) (see Figure 1.1).

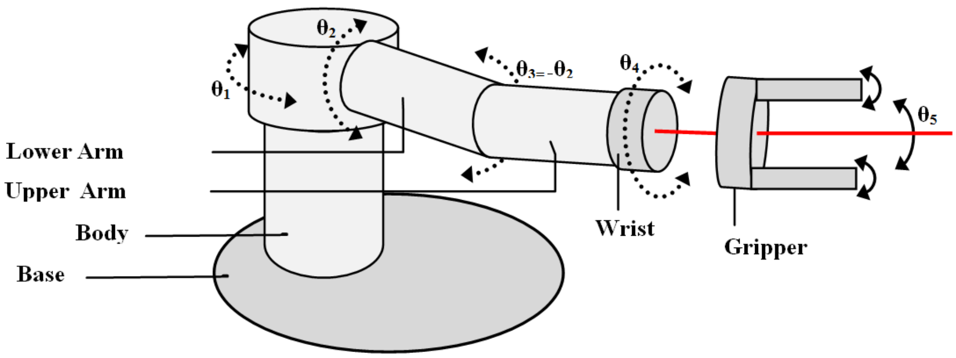

Figure 1.1 : Robot manipulator type: EDARM ED-7100

1.1.2 Wireless Communication with an Industrial Robot Manipulator

Generally, communicating with a robot manipulator is rather difficult, particularly when the robot manipulator is located far from the controller because of the long delays in the communication link. Hence, wireless technology has been widely used over the last few years in automation in solving this problem.

Various wireless technologies with wide flexibility have been developed and implemented, such as radio-frequency (RF) Zigbee, Bluetooth and WiFi or remote desktop technologies, to address different application requirements. Several wireless sensor applications have been developed in the field of moving object localisation, positioning, monitoring and tracking. Therefore, different localisation systems have been developed, analysed and implemented (Arrazola et al., 2009; Dalef et al., 2016).

1.1.3 Virtual Environment (VE)

Modern machines have now become advanced devices for automation and advanced feedback through committed control computers. This is because, computers allow the full or partial automation of complex systems and can help make manual control secure and exact. Constant information from the procedure is accessible, and numerous parameters can be intuitively controlled through the computer interface. A computer uses different programs of virtual environment (VE) for simulating and modelling a physical manufacturing system to design a completely digital factory, which is called virtual manufacturing (VM). VM is an integrated, synthetic environment that is implemented to enhance all levels of decision and control, and it involves the use of a desktop virtual reality (VR) and augmented reality (AR) systems for the computer-aided design (CAD) of components and manufacturing processes (Depince et al., 2004). The control computer provides real-time access to relevant measurements from the process, such as orientation, tool position, current operation, revolutions per minute (rev/m), temperatures and other values that are of interest to the operator, whilst the program is running (Kalpakjian et al., 2008; Wasfy et al., 2005).

1.1.4 Modelling of DC Servomotor

Every joint in the robot manipulator is driven by a servomotor. These servomotors are located at the fingers, wrist, joints of arm and the rotatable platform. DC servomotors are popular actuators in the field of robot manipulators because they are easy to use and are low cost (Schwarz et al., 2013). It is preferred in control systems because it provides continuous motion unlike the stepper motor, which produces motion in steps. A mathematical model of a DC servomotor is derived to analytically observe and define the control mechanism (Serdar, 2014).

A DC motor is a common actuator used in control systems. It directly provides rotary motion and can produce translational motion when coupled with wheels or drums and cables. The electric circuit of the armature and the free-body diagram of the rotor are shown in Figure 1.2 (Craig, 2004; Spong et al., 2004; Wada et al., 2009):

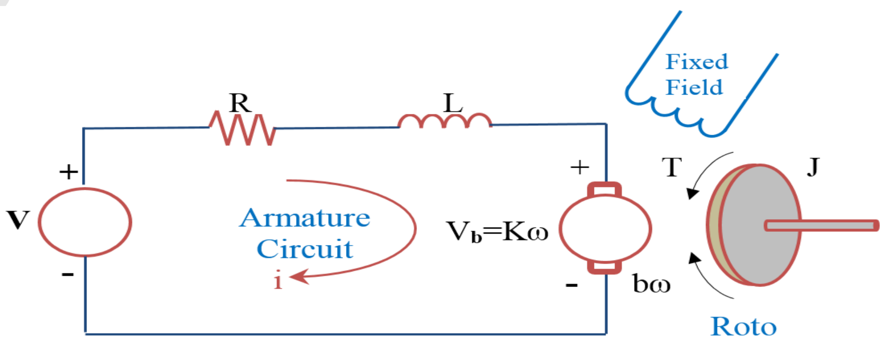

Figure 1.2 : Schematic representation of the considered DC motor

The DC servomotor model shows the relationship between the current and the torque, which causes the shaft of the motor to spin, and we have a relationship between this spinning to the Back EMF (electromotive force – Km). The rotor and the shaft are assumed to be rigid. A mathematical statement that describes the transfer characteristics of a system or equipment is called a transfer function. It shows the relationship between the input and the output of a system and uses to control position (Munadi et al., 2015). A nonlinear least squares method that controls the algorithm is designed to compute individual predictions by incorporating the receding horizon principle. While nonlinear least squares can be used to devise a strategy for finding the best fit values of the unknown parameters of the DC servomotor. As the name suggests, a nonlinear model is any model with a functional part that is nonlinear with respect to unknown parameters. Its form of least squares analysis is used to fit a set of m observations with a model that is nonlinear in an unknown parameter ($m > n$). The method is used in some forms of nonlinear regression. The method approximates the model using a linear one and refines the parameters via successive iterations (Battes et al., 2004).

1.2 Problem Statement

Current manufacturing processes are witnessing an enormous technological development in the field of intelligent industries. However there are many industrial robots still suffer many critical and harmful problems. The most prominent problems manifested during the manufacturing process, training or maintenance is the difficulty of monitoring the industrial robots. Some industrial robots work under hazardous circumstances, such as in nuclear or chemical reactors, which are too dangerous for humans to handle directly or touch these material (Sakurai, 2012). Complexity of the hardware and software of robot manipulator increases the industrial accidents. Many hazardous accidents have been associated with robot manipulator operations due to malfunctions (loose connections or faulty electronics) which it caused a rapid motion of robot manipulator in an erroneous trajectory. Where the total number of fatalities was 4,585 and over 1,300 employees were injured by moving objects in their workplace in 2013 in United States alone (BLS, 2015; OSHA, 2016; Yap et al., 2014).

Furthermore, the possibilities of deformation of mechanical part during the manufacturing process is not always taken into account during the design and programming stages, where some of the material's properties change over time because of different factors, such as accumulated stresses, joints wear and bearings wear in the devices. These changes are invisible physically and affected the parameters of a control system that depended on the feedback data and subsequently lead to different production defects like rupture or wrinkles, which subjected to time and financial loss (Eskandari et al., 2013; Vanleeuw et al., 2015). For instance, (Davarpanah et al., 2015) had mentioned different types of defects (60% tearing, 20% gulling and 55% wrinkling) in the production of machined sheet of polymers as funnel shaped as shown in Figure 1.3.

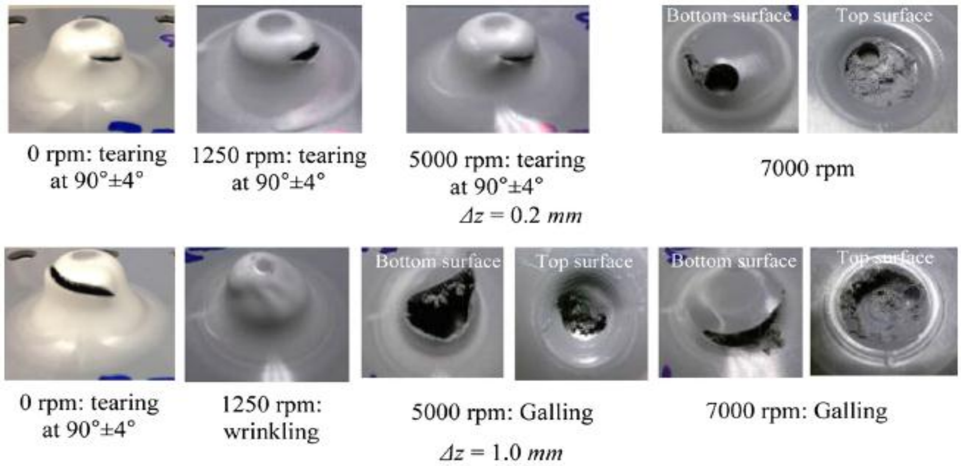

Figure 1.3 : Different defects in the funnel shaped (Davarpanah et al., 2015)

The most important problem is the unpredictable rapid deflection of robot manipulator that is caused by incorrect value of the joint's angle deviation at limited time. Therefore, there is a need for a virtual environment system which can provide convenience and intuitive robot manipulator control with independence user's location, easy adjustment and simultaneous monitoring of robot motion tasks. Furthermore, the correct timing and efficient operation are essential factors in order to predict the position and time errors of the trajectory before run the manufacturing operation.

1.2.1 Research Gap

Most of the previous studies had focused more on simulation of robot manipulator's trajectory to improve the status of trajectory by constructing different virtual environments for robotic manufacturing cell design and training. For example, (Daneshjo et al., 2018) investigated the 3D model and its interpretation in a relevant form to enable data processing with modern computer graphics techniques, and Table 1.1 clarifies other works that studied the status of trajectory.

Table 1.1 : Limitations previous related studies of monitoring robot manipulator's trajectory in VE

Ref.	Purpose	Limitations of monitoring robot manipulator's trajectory in VE			
		Simulation		Training Program	Monitoring On-line
		On-Line	Off-line		
Fang et al. 2012	Create a list of control points interactively on a parameterized model			✓	
Gaschler et al., 2014	Augmented reality system to define virtual obstacles and specifying tool positions		✓	✓	
Yap et al., 2014	A simple and user-friendly interfaces model for inexperienced users to generate robot commands		✓	✓	
Singh et al., 2015	Find the position vectors of robot and joint angles		✓		
Adewusi 2016	Identify the mechanical and electrical parameters (mass moment of inertia, damping, armature resistance and motor constant) of the motor		✓		Match simulated and measured responses above 1.5 sec. only
Chao et al., 2016	A simple interface for 3D position estimation of a mobile robot	✓			Estimate 3D coordinates of position
Myint et al., 2016	A position control and place robot arm for object sorting system	✓			High angular position error (2% - 7.3%)
Nathanael et al., 2016	A virtual reality system to support training of industrial robots to be able supporting the training novices in an entry level task in a few minutes	✓		✓	
Gogouvitis et al., 2017	A sample application covering the training to selecting, positioning and programming a 6R robotic arm		✓	✓	
Proposed work	Robotic manipulator monitoring trajectory system in VE	✓		✓	✓

Furthermore, (Akli et al., 2014) presented an analysis of a mobile manipulator movement performing a pick-up task, and (Bock et al., 2016) who studied and compared some approaches to trajectory generation for an articulated robot with six degrees of freedom. While, other works constructed and developed various systems of VEs to support training in off-line/on-line programming of industrial robots (Gogouvitis et al., 2015; Nathanael et al., 2016; Yap et al., 2014).

However, there are several knowledge gaps which restricted the control and monitoring of the deflection of the robot manipulator's trajectory during the manufacturing process in virtual environment. There is a substantial lack of knowledge with regard to control and monitoring the process to achieve the desired accuracy and precision of trajectory path. In addition, most of the difficulties that involved safety and dependability are not being solved yet in those works.

1.3 Objectives

The aim of this research is to develop a robotic manipulator monitoring trajectory system in Virtual Environment. Therefore, the objectives that need to be satisfied in respect to fulfilling the overall aim of the research are:

1. To develop a wireless control system for monitoring robot manipulator trajectory.
2. To develop an integrated virtual environment system by combining a graphical user interface (GUI) and a physical robot manipulator.
3. To derive a mathematical model and parameter simulated based on VE data to describe the trajectory of robot manipulator.

Evaluated an intelligent device is vital to the success of the project and safety of the operators by running at virtual environment before it is fully operational. Simulation of manufacturing systems is processes in virtual environment involve interaction with the robot manipulator that performs different trajectories (periodic and spiral). Simulate this activity in a virtual environment will require designing a 3D wireless sensor network technology to enhance the effectiveness of this process and to keep pace with physical movements of robot manipulator.

Describe the proposed system and predict its performance, a mathematical model, with parameters simulated of system components and experimental measurements, is required. It is essential to get this data for every joint of robot to have a complete overview of the technology that help the industrialists, researchers and developers to effect learning and training especially for maintenance process.

1.4 Scope of the Research

This research focuses on the development of robot manipulator monitoring trajectory system in virtual environment. Particularly, the research includes the difficulties of monitoring the robot manipulator trajectory of a manufacturing machine in hazardous environments, by means a model of the robot manipulator that can remotely monitoring its movements through information transfer that will be displayed in front of the user in a real-time. The wireless protocol was used to keep the compatibility of the movement between the physical robot and the virtual environment maintained by selecting suitable communication nodes with X-CTU software. This work covers complexity of the hardware and software by using a 3D-based Robotics Toolbox in MATLAB graphics that provided a visible platform for the kinematic model of the selected robot manipulator (EDARM ED-7100), and this model depends on the parameters of Denavit-Hartenberg (DH) conventions. Furthermore, to validate the hardware model measurements by a reference, a simulation model with Simulink MATLAB was designed, and optimized the parameters by using at least two parameters simulated techniques supposed to be discussed to achieve this target such as the Nonlinear Least Squares and gradient descent methods. As a final point, the scope of research also covers a comprehensive comparison with VE data and other previous works which were presented in the literature review to validate simulation model.

However, proposed system in VE for this system has a few limitations. The wireless controller system depends on zigbee protocol and does not take place online with WiFi. In addition, the feedback data and the parameters of DC servomotor for the end-effector's joint have not taken in experimental.

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LIST OF PUBLICATIONS

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