الجامعة الإسلامية العالمية ماليزيا
INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA
يونيۏرسيتي إسلام انتارابڠسا مليسيا

OPTIMAL TRAJECTORY AND GENETIC ALGORITHM BASED ENERGY MINIMIZATION FOR ROBOT MANIPULATORS

BY

MOHAMMAD YOUSEF MUSTAFA SA'ADEH

INTERNATIONAL ISLAMIC UNIVERSITY
MALAYSIA

2007

OPTIMAL TRAJECTORY AND GENETIC ALGORITHM BASED ENERGY MINIMIZATION FOR ROBOT MANIPULATORS

BY

MOHAMMAD YOUSEF MUSTAFA SA'ADEH

A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science (Mechatronics Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

JULY 2007

ABSTRACT

Robotic Manipulators are playing the great role in any successful industry nowadays. Several categories exist to classify these manipulators, Rigid or Flexible manipulators is one classification. This work investigates both types, rigid and flexible, in terms of Mathematical Modelling, Trajectory Selection, and Optimal Trajectory Planning. Optimization of trajectory can be achieved using several criterions, such as: minimum time trajectory, minimum velocity and acceleration, minimum residual vibration, or minimum energy consumed. GA will search for the trajectory that will best satisfy the objective function set by the requirement of the application. First, a three D-O-F planar redundant manipulator that is working in the joint space is proposed, and the torques of the three joints have been simulated using Soft motion and Linear Segment with Parabolic Blends (LSPB) trajectories. Then, the proposed planar manipulator has been investigated in terms of optimal trajectory planning in the task space. The manipulator's end-effector was required to track two specified paths, a straight line and a circle. The angle that the last link makes with the horizontal line was assumed to endure a Cubic Spline trajectory while tracking both paths. GA was implemented to obtain the optimal trajectory by selecting the proper initial and final configurations of that angle. Finally, a Two-Links Flexible Manipulator is modelled and analyzed. It is required to optimize the actuators' energy consumption when the manipulator performs a certain movement in the joint space. Soft motion trajectory, which is a fully identified trajectory, is employed here also to benchmark any results resulting from a less identified trajectory as the fourth order polynomial trajectory. The fourth order trajectory's parameters are obtained using GA such that the resulting trajectory is the optimal one. The simulation results verified the effectiveness of GA, since the optimized fourth order polynomial trajectory needed less energy than the soft motion trajectory when the same movement is executed.

ملخص البحث

في هذا الوقت، يلعب الإنسان الآلي دوراً أساسياً في الصناعات النّاجحه. يوجد العديد من التّصنيفات للإنسان الآلي، واحدى هذه التّصنيفات هي الإنسان الآلي الجاسئ والمرن. هذا البحث يتحرى هذين النّوعين من التّصنيفات من حيث الشّكل الرياضي، اختيار المسار، واختيار المسار الأمثل. توجد عدة معايير لاختيار المسار الأمثل، منها على سبيل المثال: المسار الذي يستغرق أقلّ وقت لإتمامه، الذي يتطلّب أقلّ سرعة وتسارع، الذي ينتج عنه أقلّ إهتزاز، أو الذي يتطلّب أقلّ طاقة مستهلكة لإتمامه. المسارات المرجوةُ من هذا البحث هي المسارات المثلى التي تتطلّب أقلّ طاقةٍ لإتمامها من مجموعة المسارات الأخرى المتاحة والممكنة. الطّريقة الجينية هي أسلوب بحث يحاكي ميكانيكية الطّبيعة في الاختيار، لهذا هي قادرةٌ على إيجاد الحلول المثلى للمعادلات اللاّخطية المعقّدة، كما هو الحال بالنّسبة للمعادلات في هذه الدراسة. هذه الطّريقة ستقوم باختيار المسارات التي تلبي اقتران الغاية الموضوع ليعكس حاجة التّطبيق، وهو أقلّ طاقة مستهلكة. أولا، تم إختيار إنسان آلي ذو ثلاثة وصلات جاسئة يتحرك في المجال المفصلي، ثم تمت محاكاة أداء العزم الناجم عن المفاصل الثلاثة باستخدام مسارين هما مسار الحركة السلسة، ومسار القطعة المستقيمة ذات الانعطافين التربيعيين. بعد ذلك، تم رسم المسار الأمثل لإنسان آلي يتحرك في المجال الأدائي. الوظيفة المناطة بيد الإنسان الآلي هي تتبع مسارين معرفين: خط مستقيم ودائرة في نفس الوقت الذي تتغير فيه الزاوية المحصورة بين الضلع الأخير والمستوى وفقا لمسار ثلاثي القوة. تم تطبيق الطريقة الجينية لاختيار المسار الأمثل عن طريق اختيار القيمة الابتدائية، والنهائية لتلك الزاوية. أخيرا، تعرضت الدراسة لإنسان آلي ذو ضلعين مرنين. المطلوب تقليل طاقة المحركات اللازمة لأداء حركة في المجال المفصلي. المفترض أن تتم الحركة باستخدام مسار الحركة السلسة بالإضافة إلى مسار رباعي القوة . سيصار إلى اختيار حدود المسار رباعي القوة باستخدام الطريقة الجينية لتحقيق المسار الأمثل. النتائج المقدمة تثبت فاعلية الطريقة الجينية وتميزها، حيث إن المسار الناتج هو مسار يلزمه طاقة أقل.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Mechatronics Engineering.

……………..…………………….....
Atef A. Ata
Supervisor

……………..…………………….....
Waleed F. Faris
Supervisor

I certify that I have read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Mechatronics Engineering.

……………..…………………….....
Wahyudi Martono
Internal Examiner

……………..…………………….....
Shamsudin Amin
External Examiner

This dissertation was submitted to the department of Mechatronics Engineering and is accepted as a partial fulfilment of the requirements for the degree of Master of Science in Mechatronics Engineering.

……………..…………………….....
MD Raisuddin Khan
Head, Department of
Mechatronics Engineering

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as a partial fulfilment of the requirements for the degree of Master of Science in Mechatronics Engineering.

……………..…………………….....
Ahmad Faris Ismail
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degree at IIUM or other institutions.

Mohammad Yousef Mustafa Sa'adeh

Signature …………………………………....   Date…...…………………

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DELCLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

OPTIMAL TRAJECTORY AND GENETIC ALGORITHM BASED ENERGY MINIMIZATION FOR ROBOT MANIPULATORS

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without the prior written permission of the copyright holder except as provided below.

1. Any material contained in or derived from this unpublished research may only be used by others in their writing with due acknowledgement.

2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional academic purposes.

3. The IIUM library will have the right to make, store in retrieval system and supply copies of this unpublished research if requested by other universities and research libraries.

Affirmed by Mohammad Yousef Mustafa Sa'adeh

………………………………… ………………………
Signature Date

To my beloved parents..

..brother and sisters..

..and my beloved wife

ACKNOWLEDGEMENTS

At the very outset, all my prayers and thankfulness are to Allah the almighty for facilitating this work and for granting me the opportunity to be surrounded by great and helpful people at IIUM.

I would like to express my everlasting gratitude to my supervisors, Dr. Atef A. Ata and Dr. Waleed F. Faris for their invaluable encouragement, guidance and monitoring, without which this work would not have reached the point of fruition, so I ask Allah to reward them on my behalf.

I would never have attempted to obtain a post-graduate degree if it weren't for the continuous encouragement that I received from my father, Prof. Yousef M. Sa'adeh, the man to whom I will be grateful, for the rest of my life.

The warm heart, my mother, deserves all the credit here; she has been a source of inspiration to me for years. I would never forget her continuous prayer for the sake of my success.

No acknowledgement would be complete without expressing my appreciation and thankfulness for my wife; I can't refute her long lasting patience and support which she showed during this work and which was essential to accomplish it.

My siblings, to whom I belong, have shadowed me with their concern all the time, so they deserve my acknowledgement too.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

l	Manipulator's Link Length
I	Mass Moment Of Inertia
m	Mass of Link
g	Acceleration Of Gravity
K	Kinetic Energy of a System
P	Potential Energy of a System
L	The Lagrangian
q	Generalized Coordinate
Q	Generalized Force
T	Joint's Torque
t_b	Trajectory's Blending Time
θ	Joint's Angular Displacement
ω	Joint's Angular Velocity
α	Joint's Angular Acceleration
J	Joint's Jerk
ϕ	Angle between the Final Link and the Horizontal Axis
PI	Performance Index
p	Penalty Function
$w(x,t)$	Transverse Elastic Displacement of a Flexible Link
$\xi(t)$	Time Function
$W(x)$	Mode Shape
r	Position Vector
ρ	Mass Density per Unit Length
EI	Flexural Rigidity
δW	Virtual Work Done by Joint's Torque
ω_n	Beam's Natural Frequency
βl	Beam's Normal Mode

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

The increase demand on robotic applications has magnified and highlighted the importance of studying different aspects concerning robots. Robots received major attention by researchers in the 20^{th} century due to its successful implementation in industry and, later on, in space; the work done in this area witnessed several outstanding achievements due to the need of real time robotic applications. Trajectory planning was one of the early works in this field and a range of trajectories are nowadays available for different industrial applications. Trajectory selection is crucial since different trajectories have different characteristics, also different robotic applications have different requirements and constraints such as; minimum time, maximum velocity and acceleration, obstacle avoidance, minimum energy consumed, and so on.

Since the availability of energy is limited in some circumstances especially in space, energy-optimized trajectories as well as light weight (flexible) manipulators have been always in great demand. The importance of such manipulators rose from several facts, such that they have high payload to manipulator weight ratio, also they need less energy to run due to their relatively low weight, which is in fact a big advantage since energy consumption is a major drawback that faces some applications, as in space missions. Furthermore, the reachability of these manipulators is higher due to the ability to use long links. On the other hand, many complexities are associated with the use of light weight manipulators, such as modelling and vibration issues, and this is due to the flexibility of the links and sometimes the joints.

In industry, heavy weight manipulators are primarily used due to their capabilities in handling applications while achieving accurate movements; in addition, the vibration issues are very limited and can be easily eliminated, but the energy consumption remains a primary defect of such manipulators. Unlike rigid manipulators, flexible manipulators involve more complex and challenging work, especially at the modelling stage where the flexibility of the links will raise both, the number and complexity, of equations of motion and as a result will raise the difficulty of solution. For instance, the implementation of light weight manipulators in industry is limited. As mentioned earlier, the defects of light weight manipulators are limiting their use in industrial works; yet, this is a hot area in research, and several works have been carried out on this topic, and most of these works were concentrated on the vibration suppression problem.

1.2 PROBLEM STATEMENT

Many robotic-based industrial applications do not consider the three D-O-F planar redundant manipulators despite these manipulators are good candidates for optimization purposes. This work deals with the three D-O-F manipulators from two prospective points. First, trajectory planning, and second, optimal trajectory selection.

Trajectory planning for planar redundant manipulators covers a wide range of trajectory profiles. Soft motion trajectory is a relatively new profile which has not been benchmarked with any other trajectory by researchers. This work comes to investigate the soft trajectory and compare it with other known profiles so that the characteristics of the soft trajectory is better understood and discussed.

Optimal trajectory selection has been always a demand in many industrial applications. Thus, the work introduced here assumed that the manipulator's end-effector is required to perform two tasks optimally. Then, an objective function is introduced and optimal trajectory profiles are finally selected.

Two links flexible manipulator is also considered. The mathematical modelling of the flexible manipulator is difficult to be obtained directly from the equations of motion, since the resulting equations of motion are highly nonlinear integro-partial differential equations, and it is almost impossible to solve such equations analytically. Instead, it was assumed that the links can be treated as Euler-Bernoulli's beams and that the boundary conditions are similar to those obtained from these beams.

Optimal trajectory selection was required to validate the effectiveness of the method used, thus soft motion and optimal fourth order polynomial trajectories were tested and compared. To study the effect of changing the boundary conditions, different boundary conditions were used and the resulting outputs were compared and analyzed.

1.3 OBJECTIVES OF THE STUDY

The objectives of this research are as follows:

- To study the effect of different path trajectories on manipulator's joints torques.

  The joints' torques of the three D-O-F planar manipulator are to be simulated using two different trajectories. Linear Segment with Parabolic Blends (LSPB) and Soft Motion trajectories are compared here and simulation results are introduced.

- To optimize the energy needed to run a three D-O-F planar manipulator.

Genetic Algorithm (GA) is applied here to find the optimal trajectory for a three D-O-F manipulator. The end-effector of the manipulator is required to follow a specified path while enduring a certain trajectory. Using inverse kinematics, the individual joints angles, angular velocities, as well as angular accelerations are determined.

- To apply the Genetic Algorithms technique for optimal trajectory planning for two-link flexible manipulator.

  Again, Genetic Algorithm will be used here to search for the optimal, energy minimized trajectory. The manipulator is mathematically represented using extended Hamilton's principle, and the flexible links are treated using Euler-Bernoulli's beam theory. A comparison between soft motion and optimal fourth order polynomial trajectories will be carried out to show the significance of Genetic Algorithm and to verify the effectiveness of the method used.

- To study the effect of different combination of beam's boundary conditions on the performance of the flexible manipulator.

  Different combinations of beam's boundary conditions, when applied to the same system, will result in different outcomes. In this work, the Fixed-Free and Pinned-Free boundary conditions are assumed, and the effect of using these combinations is highlighted and introduced.

1.4 SCOPE OF THE THESIS

This research covers many aspects concerning robotic manipulators. For the rigid manipulator, mathematical modelling and trajectory planning as well as optimal trajectory selection are discussed. The manipulator is modelled using Lagrange approach where generalized coordinates and generalized forces are assumed. Trajectory planning for a 3 DOF planar redundant manipulator, which is working in the joint space, is discussed. Two trajectories are used and their corresponding generated output torques are compared. Task space is also presented as a manipulator is required to track two specified paths optimally.

Two links flexible manipulator is also introduced. The mathematical modelling is derived using the extended Hamilton's principle and the links are treated using Euler-Bernoulli's beam theory. The manipulator is assumed to be working in the joint space, where certain joints' movements are required. Optimal trajectory planning is addressed as two different trajectories are used to generate the required movements. Different boundary conditions are also presented and the resulting output torques are compared.

1.5 RESEARCH METHODOLOGY

At the beginning, a 3 D-O-F planar redundant manipulator that is working in the joint space is studied. The actuators torques are simulated using different trajectory profiles, such as: soft motion trajectory and linear segment with parabolic blends trajectory. The manipulator is then assumed to move in the task space. Two paths are required to be followed by the manipulator's end-effector, a straight line and a circle. It is required that the angle between the last link and the horizontal line to satisfy a cubic spline trajectory while tracking these paths, also it is required that the generated trajectories be optimal ones.

Two links flexible manipulator is then studied. The two links are assumed to be homogeneous and equal in length. The mathematical modelling for the manipulator is derived using the extended Hamilton's principle and the links are treated as Euler-

Bernoulli's beam theory. The manipulator is required to perform a certain movement optimally. So, soft motion and optimized fourth order polynomial trajectory are compared in terms of the manipulator's generated torques and the overall energy needed to perform the movement.

The effect of using different boundary conditions on the flexible manipulator's torques is addressed too. Fixed-free and pinned-free boundary conditions are assumed, and the generated output torques are introduced and compared.

1.6 THESIS OUTLINE

This thesis consists of six chapters. Chapter two introduces some Evolutionary Algorithms, and concentrates on Genetic Algorithms (GA) which is the optimization technique used throughout this work. The function and the parameters forming GA are introduced, as well.

Chapter three investigates a three D-O-F redundant planar manipulator. The mathematical modelling of the proposed manipulator is first derived using Lagrange's approach and the three equations describing the torques of the joints are given. The three joints' torques are then simulated using LSPB and Soft Motion trajectories; simulation results for angles, velocities, accelerations, and torques profiles for both trajectories are presented and compared.

While in Chapter four, an energy minimized, optimal motion trajectory for a three D-O-F redundant planar manipulator is required while the end-effector of the manipulator tracks two predetermined paths, a straight line and a circle. The angle that the last link makes with horizontal ϕ is required to undergo a third order polynomial trajectory, the starting and goal angle values are left undetermined. GA is employed to search for these values such that an optimal trajectory is satisfied. Geometric approach