DESIGN AND CONTROL OF PARALLEL ROBOTS BASED ON DTC AND DFC DESIGN METHODOLOGIES

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ABSTRACT

The project aims to evaluate the effectiveness of "Design For Control" (DFC) methodology against "Design Then Control" (DTC) methodology experimentally via real time tests. To achieve this, two 5-bars parallel robots have been constructed. Each has two degree-of-freedom. The first parallel robot adopts DTC, a traditional sequential design approach. The second parallel robot adopts DFC, a concurrent mechatronic design methodology.

This paper details the design and control of both parallel robots. It is divided into five sections: section 1 presents an introduction for the project, section 2 details a literature review on the needs of carrying out this project, section 3 describes theoretical works that have been studied, section 4 presents experimental study that have been carried out up to this stage. Finally, the paper is summarized and suggestions for future works are presented in section 5

Keywords: Parallel Robot, Mechatronic Design Methodology, Design Then Control, Design For Control

1. INTRODUCTION

1.1 Types of Robot

In general, robots can be categorized into three main groups based on their mechanism: serial, parallel and hybrid. Serial robots typically have open kinematic chain and sequentially connected links. On the other hand, parallel robot is a closed chain mechanism, which consists of two platforms (base and end-effector), connected together by at least two independent, parallel kinematic chains. Meanwhile, hybrid robots consist of a combination of open chain and closed chain mechanisms

1.2 Design Methodologies

In this project, two parallel robots have been constructed. There are two design methodologies applied to the construction of these robots, namely Design Then Control (DTC), and Design For Control (DFC). The first parallel robot adopts DTC, a traditional sequential design approach. The second parallel robot adopts DFC, a concurrent mechatronic design methodology.

DTC is the traditional design approach in designing mechatronic system as illustrated in Figure 1. The approach emphasizes sequential design – mechanical design is considered prior to controller design. As both the mechanical structure and control system are dependent on each other, designing one without taking into consideration the other leads to a mechatronic system that is non-optimal in performance [1]. Apart from that, one might also end up with a control system that is highly complicated and undesirable.

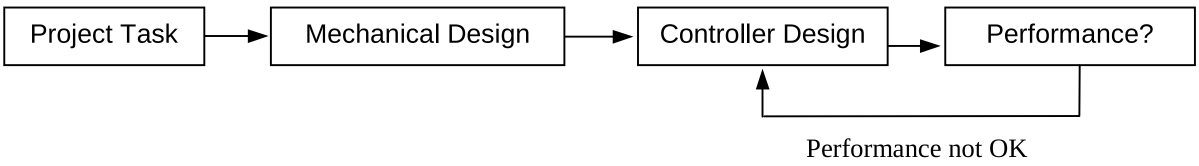

Figure 1: DTC Design Methodology

On the other hand, DFC suggests a concurrent engineering design approach – controller design is taken into consideration at the stage of mechanical design as illustrated in Figure 2. The underlying idea of DFC is to obtain simple dynamic model of the mechanical structure such that its control algorithm can be easily implemented in real time.

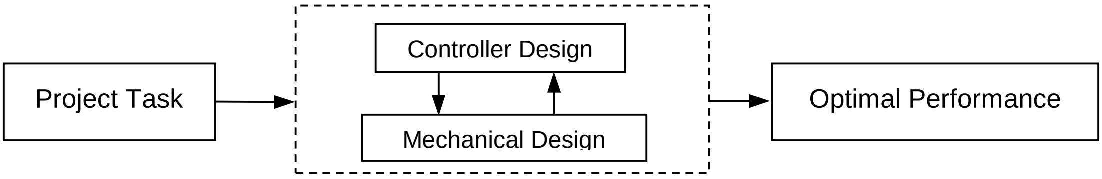

Figure 2: DFC Design Methodology

1.3 System Overview

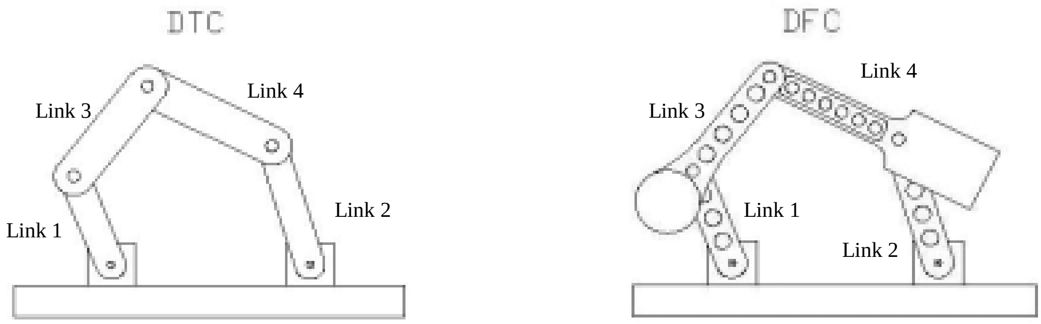

Figure 3.a

Figure 3.b

Figure 3: Parallel robots based on DTC and DFC design methodologies

The parallel robot shown in Figure 3.a was constructed to implement the DTC design methodology. All the links of the DTC robot are made of Aluminium bars. Meanwhile, Figure 3.b depicts the parallel robot that was built based on DFC design methodology. In this structure, link 1 and link 2 are made of Aluminium bars while link 3 and link 4 are made of Perspex material. Details of structural parameters can be found in Table 1 in Section 3. Both parallel robots consist of 5 linkages (include one virtual linkage). Link 1 and link 2 are attached to the rotating shaft of the motors while link 3 and link 4 are joined together by the end effector. Both robots will be controlled using PID control algorithm.

2. LITERATURE REVIEW

During the past two decades, increased interest in parallel robots has been observed. This is due to its advantages over serial robots. Features such as high rigidity and large load-to-weight ratio allow parallel robots to manipulate in a more precise and faster manner. However, the control of a parallel robot using traditional DTC approach often raises difficult problems to control engineers. This is due to the following problems [2]:

- Dynamic model of a parallel robot is much more complicated than the serial robot. The complex dynamic model is very difficult to be calculated in real time and implemented physically, particularly for high-speed application.
- Although simplification techniques have been used to obtain simplified dynamic model and thus avoid heavy computation, performance accuracy suffers due to modelling errors.

To overcome these problems, DFC design methodology has been proposed. DFC suggests that simplification of the dynamic model of a mechatronic system can be accomplished by proper design and selection of mechanical geometrical parameters [3]. The aim of DFC is to facilitate the controller design. The effectiveness of this design methodology has been successfully demonstrated in the implementation of a four-bar linkage [4] and a 2 degrees-of-freedom parallel robot [2] via simulation studies. Nevertheless, there is no experimental proof of the effectiveness of DFC against DTC design methodology. Hence, the project aims to address the gap in this research area by carrying out real time tests on the constructed parallel robots by comparing their performances.

3. THEORETICAL WORK

Table 1 summarizes the dynamic models of both parallel robots derived using Lagrangian method [2].

DESIGN METHOD	DYNAMIC MODELS	STATUS
DTC METHODOLOGY	$D(q')\ddot{q} + C(q',\dot{q}')\dot{q} + g(q') = \tau$	*Highly complicated*
DFC METHODOLOGY	$\overline{D}(q')\ddot{q} + \overline{C}(q',\dot{q}')\dot{q} = \tau$	*Simplified model*

Table 1: Dynamics models of the Parallel Robots

The dynamic model of the parallel robot designed using DTC design methodology consists of three terms: Inertia term $D(q')\ \ddot{q}$, Coriolis term $C(q',\dot{q}')\ \dot{q}$, and Gravitational term $g(q')$, as indicated in Table 1. The dynamic model is complex, highly non-linear and highly coupled. It is difficult to design a control algorithm based on this model. In order to reduce the complexity of the controller design, the parallel robot has been redesigned using DFC methodology. The idea of DFC is to simplify the dynamic model of the parallel robot to the most extend without varying the topology of the parallel robot. This can be accomplished by reducing all three terms in the dynamic model of the original parallel robot (DTC case).

As a result, the first parallel robot (DTC case) is constructed by considering only workspace criterion (100mm $\times$ 100mm) and mechanical constraints. Meanwhile, the second parallel robot is built by applying DFC solution presented by Li and Wu [2]. In their paper, the idea of DFC methodology is implemented on a parallel robot (Figure 4) by fulfilling the following conditions:

1. $r_3 = r_4 = 0$
2. $Ji_{DFC} < Ji_{DTC}$ for i = 1, 2, 3, 4
   where Ji = mass moment of inertia with respect to the centroid of link i.

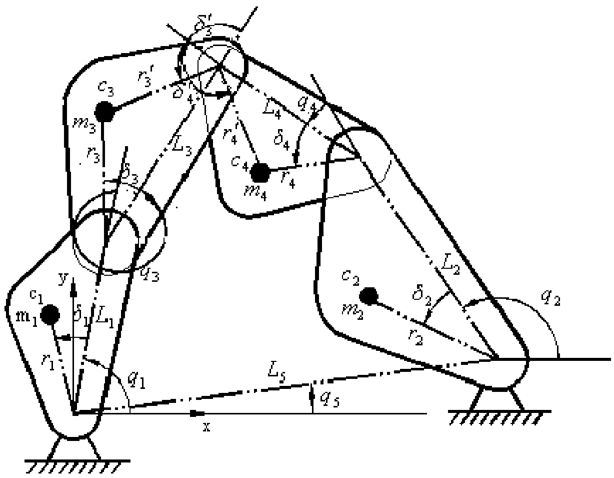

Figure 4: Structure of a 2 degrees-of-freedom Parallel Robot (adapted from [2])

According to Li and Wu [2], gravitational term can be eliminated from Lagrange's equation describing the parallel robot by satisfying condition 1. To further simplify the dynamic model, condition 2 is imposed such that inertia term is reduced. As a result, a less complex dynamic model is obtained and simple PID control algorithm can be used to control the robot motion. Thus, the second parallel robot has been designed in an iterative manner such that it fulfills both conditions as well as workspace criterion and mechanical constraints. A summary of structural parameters for the final design of both parallel robots is presented in Table 2.

Parameters	**DTC**	**DFC**
L_1 (m)	0.100	0.100
L_2 (m)	0.130	0.130
L_3 (m)	0.120	0.120
L_4 (m)	0.140	0.140
L_5 (m)	0.200	0.200
r_1 (m)	0.050	0.050
r_2 (m)	0.065	0.065
r_3 (m)	0.060	0.000
r_4 (m)	0.070	0.000
m_1 (kg)	0.098	0.080
m_2 (kg)	0.123	0.100
m_3 (kg)	0.189	0.112
m_4 (kg)	0.215	0.108
J_1 ($x10^{-3}kg.m^2$)	0.132	0.124
J_2 ($x10^{-3}kg.m^2$)	0.248	0.238
J_3 ($x10^{-3}kg.m^2$)	0.380	0.363
J_4 ($x10^{-3}kg.m^2$)	0.543	0.535

Table 2: Comparison in Design Variables (DTC vs. DFC)

4. EXPERIMENT STUDY

4.1 Experiment Setup

After the construction of both parallel robots have been completed, real time tests are carried out to examine the effectiveness of DFC against DTC design methodology. Figure 5 illustrates the experimental setup for the tests.

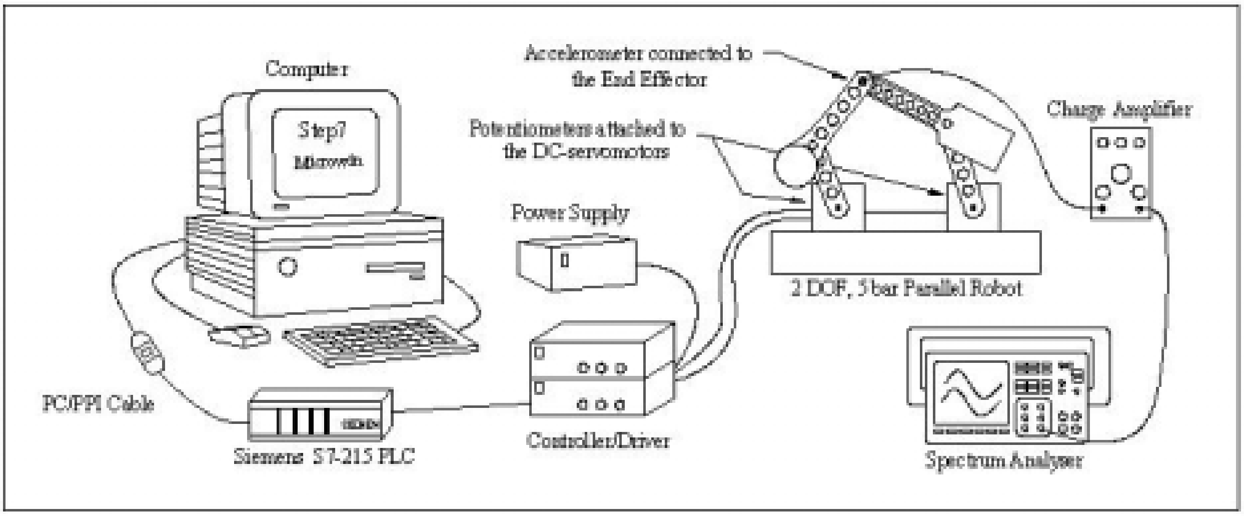

Figure 5: Experiment Setup for the real time tests

The parallel robot is actuated by two direct drive DC-servomotors of 1.83Nm in peak torque. The angular position of the robot links is detected by two potentiometers. The potentiometers are attached at the end of the rotating motor shafts. Meanwhile, Siemens S7-215 PLC is used to control the robot. This is accomplished via *STEP 7 – Microwin* (S7) software that is installed on a computer connected to the PLC via communication port (PC/PPI cable). A PID control algorithm is implemented using the information acquired from the potentiometers. Apart from that, an accelerometer is placed at the end effector to measure the end point vibrations. The analogue output signals from the accelerometer are amplified by charge amplifier before entering spectrum analyser for result display.

To demonstrate the effectiveness of DFC against DTC design methodologies, real time tests are conducted in such a way that performance of the following parameters can be compared:

- Vibrations level
  - Data acquired from the accelerometer will be used to compare the vibrations level of the parallel robots.
- Angular displacement errors
  - The angular positions of link 1 and link 2 are recorded at certain time interval. This is accomplished by saving the feedback readings from the potentiometers. The profiles of angular displacement errors against time for both robots are plotted.
- Linkage motion
  - A pencil is placed at the end-effector to draw a path. The paths generated by both robots will be compared.

4.2 Experiment Expectations

The real time tests are currently being conducted. As a result, the performance of both parallel robots cannot be compared and the effectiveness of DFC against DTC is not presented in this paper. Nevertheless, it is expected that the vibration level for DFC robot will be lower than DTC robot. It is also predicted that DTC robot will result in larger angular displacement errors relative to DFC robot. Furthermore, the path generated by DFC robot will be smoother than the path generated by DTC robot. Apart from that, it is expected that the time required to tune the controller for DFC robot will be much less than the time required to tune the controller for DTC robot.

5. CONCLUSION

The design and construction of the parallel robots based on DTC and DFC is presented in this paper. The expected outcomes of the real time tests for both robots are discussed. It is suggested that model-based controllers could be used instead of PID controllers for future research.

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