Karlsruher Institut für Technologie

Fakultät für Elektrotechnik
und Informationstechnik

Xiaoyi Gu

Stiffness Enhancing Action Planning for Coupled Industrial Robots in Manufacturing Processes

Master's Thesis Bxxx

Institut für Regelungs- und Steuerungssysteme
Institutsleiter: Prof. Dr.-Ing. Sören Hohmann

Karlsruher Institut für Technologie

Institut für Regelungs-
und Steuerungssysteme

Master's Thesis Bxxx

Stiffness Enhancing Action Planning for Coupled Industrial Robots in Manufacturing Processes

Aufgabenstellung von Betreuer...

Student	:	Xiaoyi Gu, M.Sc
Supervisor	:	Xin Ye, M.Sc.
Examiner	:	Prof. Dr.-Ing. Sören Hohmann
Date of hand out	:	December 31st, 2021
Date of hand in	:	August 12th, 2022

I declare that I wrote my Master's Thesis by myself and that I have followed the regulations relating to good scientific practice of the Karlsruhe Institute of Technology (KIT). I did not use any unacknowledged sources or means and I marked all references I used literally or by content.

Karlsruhe, August 12th, 2022

Xiaoyi Gu, M.Sc

Acknowledgments

Firstly, I would like to thank ...

Abstract

Here comes an abstract...

Contents

List of Figures

List of Tables

Abbreviations and Symbols

Latin letters

Symbol	Meaning
1_n	column vector of n ones
0_n	column vector of n zeros
A	discrete-time system matrix
A_i	system matrix of subsystem i
B	discrete-time input matrix
B_i	input matrix of subsystem i
C	discrete-time output matrix
D	degree matrix of a graph

Greek letters

Symbol	Meaning
α	step size of a distributed optimization algorithm
γ	tuning factor
$\sigma_{\max}$	maximum singular value
$\sigma_{\min}$	minimal singular value

Calligraphic and other symbols

Symbol	Meaning
$\mathcal{E}$	edge set of a graph
$\mathcal{G}$	directed graph

Indices, exponents and operator names

Symbol	Meaning
arg	argument of a solution of an optimization

$\mathrm{Im}A$	image of a matrix A
lim	limit of a sequence

Chapter 1

Introduction

1.1 Background and Motivation

Robots are used extensively in manufacturing, not only in the automotive industry but also in the production of the space shuttle, the development of military equipment and high-speed railways, and the production of commodities. Due to the rapid development of robotics, not only is the price gap between products becoming smaller and smaller compared to traditional industrial equipment, but also the degree of personalization of products so that industrial robots can be used to replace traditional equipment in the manufacture of some complex products, which can vastly improve economic efficiency and save energy [URH16].

The use of robots in factories can solve many safety problems. Potential safety problems for personal reasons, such as unfamiliarity with work processes, negligence, or fatigue, can be avoided.

As robotics continues to develop and advance, an individual robot can no longer perform complex and tedious tasks independently to meet the work targets in production practice, and there is an urgent need to research new directions to meet practical needs. Multiple robots working simultaneously can increase efficiency and enhance the synergy of work task indicators. Systems made up of multiple robots have certain advantages over an individual robot [Bro07].

(1) High adaptability to the environment: Compared to individual robots, multi-robot systems show greater flexibility and adaptability to work tasks, with better distribution in function and space than individual robots.

(2) Strong load-bearing capacity: A multi-robot system is a group, with each robot working individually while coordinating with the others, resulting in much shorter working times, effectively increasing productivity and a more substantial work-bearing capacity.

(3) High robustness. In multi-robot systems, task completion requires the involvement of each robot rather than relying exclusively on one robot, thus providing high fault tolerance and robustness.

Industrial robots have evolved from traditional handling, assembly, and welding tasks to a wide range of production applications. The use of robots in manufacturing processes can lead to high flexibility and low costs. However, the performance of robots is hardly comparable to that of machine tools. Stiffness is considered to be a significant weakness in robotic machining applications [AWR07].

Using two coupled robots in manufacturing provides higher stiffness than one robot. To reduce defects in robotic machining, physically coupled multi-robot systems are used. Physically coupled robots perform coordinated actions through force interactions. The end-effectors or flanges of several robots can be connected utilizing a rigid coupler. Various machining tasks, such as drilling and milling, can be implemented on the coupler by employing ratchets attached to the coupler. Most stiffness problems in robot-driven machining research have been on a single robot [Dum+12] [LZD17] [GDK15], and there is a need to extend these studies to multi-robot systems.

In order to increase the stiffness of the coupled robot, an optimization method is used to find the optimal pose of coupled robots, position, and angle of the workpiece.

1.2 Problem Definition

Definition 1 (Stiffness). *Stiffness is the extent to which an object resists deformation in response to an applied force.*

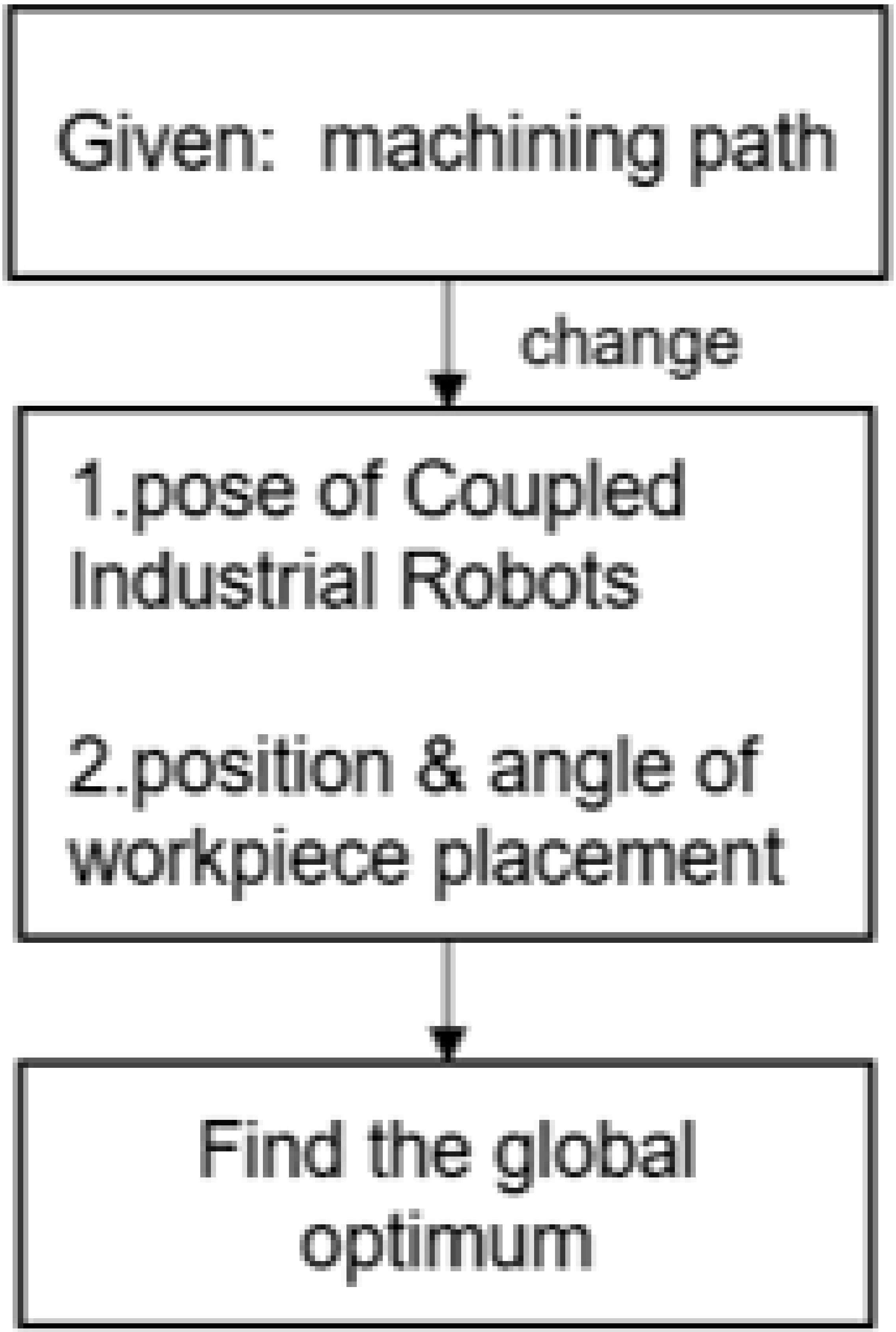

Figure 1.1: Graphical representation of the research process.

Chapter 2

Fundamentals

In this chapter...

Chapter 3

Main Part

Appendix A

Trivial Proofs

The following sections demonstrate the veracity of Figure 1.1 and (**??**).

A.1 Central Argument

Patrick is a genius.

A.2 Motivation

Careful observation.

A.3 Listings

Quellcodes lassen sich gut mit dem listings-Paket einbinden, so ist das Einbinden von entsprechend formatiertem Matlab-/C++/etc.-Code ohne Copy/Paste direkt aus der Quellcode-Datei möglich. Und hier noch ein Beispielhafter Matlab Quellcode:

```
%% State Space System
asyn.SS = ss(asyn.A,asyn.B,asyn.C,asyn.D);

% Infos über das System
disp('– Informationen über das System –');
% Ordnung des Systems
asyn.n = rank(asyn.A);
disp(['Ordnung des Systems n = ', num2str(asyn.n)]);
% Polstellen
asyn.PS = pole(asyn.SS);
% Nullstellen
asyn.NS = tzero(asyn.SS);
% Beobachtbarkeit
asyn.Ob = obsv(asyn.SS);
if rank(asyn.Ob) == asyn.n
disp('System vollständig Beobachtbar');
else
disp('System nicht vollständig Beobachtbar');
end
% Steuerbarkeit
asyn.Os = ctrb(asyn.SS);
if rank(asyn.Os) == asyn.n
disp('System vollständig Steuerbar');
else
disp('System nicht vollständig Steuerbar');
```

```
end

disp('————————————————————————————————');
```

Listing A.1: Ein wahnsinnig komplizierter Quellcode

Listings

List of Algorithms

Bibliography

[AWR07] Eberhard Abele, Matthias Weigold, and Stefan Rothenbücher. "Modeling and identification of an industrial robot for machining applications". In: *CIRP annals* 56.1 (2007), pp. 387–390.

[Bro07] Torgny Brogårdh. "Present and future robot control development—An industrial perspective". In: *Annual Reviews in Control* 31.1 (2007), pp. 69–79. ISSN: 1367-5788. DOI: https://doi.org/10.1016/j.arcontrol.2007.01.002. URL: https://www.sciencedirect.com/science/article/pii/S1367578807000077.

[Dum+12] Claire Dumas et al. "Workpiece placement optimization of six-revolute industrial serial robots for machining operations". In: *Engineering Systems Design and Analysis*. Vol. 44854. American Society of Mechanical Engineers. 2012, pp. 419–428.

[GDK15] Yingjie Guo, Huiyue Dong, and Yinglin Ke. "Stiffness-oriented posture optimization in robotic machining applications". In: *Robotics and Computer-Integrated Manufacturing* 35 (2015), pp. 69–76.

[LZD17] Yang Lin, Huan Zhao, and Han Ding. "Posture optimization methodology of 6R industrial robots for machining using performance evaluation indexes". In: *Robotics and computer-integrated manufacturing* 48 (2017), pp. 59–72.

[URH16] Eckart Uhlmann, Sascha Reinkober, and Tobias Hollerbach. "Energy efficient usage of industrial robots for machining processes". In: *Procedia CIRP* 48 (2016), pp. 206–211.