DESIGN AND OPTIMUM OPERATION OF A RE-CONFIGURABLE PLANAR GOUGH-STEWART MACHINING PLATFORM

by

Lukas Johannes du Plessis

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Dedicated to my family
and in memory of
“Oom Nap & Tannie Lalie Esterhuizen”

ABSTRACT

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Lukas Johannes du Plessis

Promoter: **Professor J.A. Snyman**
Department of Mechanical and Aeronautical Engineering

Degree: Philosophiae Doctor (Mechanical Engineering)

Keywords: Gough-Stewart platform, re-configurable machine tool, adjustable geometry, inverse kinematics, inverse dynamic analysis, trajectory-planning, cubic spline interpolation, mathematical optimization, constrained optimization problem.

This study presents a computer operating system for a novel *re-configurable planar Gough-Stewart machining platform*. The operating system is tested on a physically constructed *test-model* of the proposed re-configurable platform. In doing so, the proposed concept of a re-configurable planar machine tool, consisting of a moving platform connected to a fixed base via three linear actuators is validated, both from a theoretical and practical point of view.

The computer operating system consists of four sections:

1. **Simulation**: A computer program for simulating the motion of a planar Gough-Stewart platform was developed. This was done by applying the basic principles of Newton-Euler dynamics to a mechanical model of the platform. In particular, this special purpose simulation program allows for the *inverse dynamic analysis* of a planar Gough-Stewart platform so as to give closed-form expressions for the required actuator forces necessary for the execution of a *specified trajectory*. As a prerequisite for the inverse dynamic analysis, the special purpose program that was developed, also performs the *inverse kinematic analysis* of the mechanism by solving closed-form expressions for the positions, velocities and accelerations of the individual bodies comprising the machine.
2. **Trajectory-planning**: A new *path-planning* interpolation algorithm has been developed with which a user may specify the desired path to be followed by any *planar* industrial robot, and therefore in particular also the planar Gough-Stewart platform. Given prescribed kinematical requirements and

specified points along the path, a *cubic spline interpolation curve* is fitted in the time-domain, and further user-specified information is used to determine how the end-effector orientation angle should vary along the specified curve. This trajectory-planning algorithm is combined with the above-mentioned inverse dynamic simulation program to determine and monitor the required actuator forces as the planar Gough-Stewart platform traces the prescribed trajectory.

3. **Optimization**: With the ability to determine the required actuator forces at any instant along any prescribed path, an *adjustable geometry* planar Gough-Stewart machining platform becomes a viable option. The rationale is that the simulation of the mechanism allows for the off-line *optimization* of the operational geometry of the mechanism for the prescribed path. The single criterion objective function used is the minimization of the "maximum magnitude actuator force" identified via the above-mentioned dynamic simulation. The minimization of this objective function with respect to the variable geometry, ensures that singular configurations are avoided as the specified path is traced. The minimization of the objective function is further subjected to compliance with formulated inequality constraints that ensures mechanical feasibility as the *constrained optimization problem* is solved.

   Once the optimum operational geometry is determined, the physical re-configurable planar Gough-Stewart platform can be adjusted accordingly to ensure the successful execution of the desired trajectory. If it is not possible to trace the prescribed path, then user intervention is required. This may be done in a rational manner since the specific numerical optimization algorithm used here (LFOPC), gives a best compromised solution if no feasible design exists for the specified trajectory. The importance of this compromised solution is that it points out which constraints are violated and to what extent. This provides information for determining a piece-wise execution strategy by means of which the complete task may be performed, both feasibly and optimally.

4. **Control**: Apart from optimizing the Gough-Stewart platform configuration for a given task, the computer operating system also generates the necessary commands for controlling the required variation of the actuator leg lengths. This allowed for the physical execution of a number of representative prescribed machining paths.

SAMEVATTING

ONTWERP EN OPTIMALE WERKING VAN 'n HERKONFIGUREERBARE VLAK GOUGH-STEWART-MASJINERINGSPLATFORM

deur

Lukas Johannes du Plessis

Promotor: **Professor J.A. Snyman**
Department Meganiese and Lugvaartkundige Ingenieurswese

Graadbenaming: Philosophiae Doctor (Meganiese Ingenieurswese)

Sleutelwoorde: Gough-Stewart platform, herkonfigureerbare masjienwerktuig, verstelbare geometrie, terugwaartse kinematika, terugwaartse dinamiese analise, kubiese lat-interpolasie, wiskundige optimering, begrensde optimeringsprobleem.

Hierdie studie handel oor 'n rekenaarbedryfstelsel vir die inwerkingstelling van 'n unieke *herkonfigureerbare vlak Gough-Stewart-masjineringsplatform*. Die bedryfstelsel is getoets met behulp van 'n toetsmodel van die voorgestelde herkonfigureerbare platform, wat spesiaal vir die doel ontwerp en gebou is. Sodoende is die uitvoerbaarheid van die voorgestelde konsep van 'n herkonfigureerbare vlak masjienwerktuig bevestig, beide vanuit 'n teoretiese en praktiese oogpunt. Die herkonfigureerbare vlak Gough-Stewart-masjineringsplatform waarna verwys word, bestaan uit 'n bewegende platform wat deur middel van drie lineêre aktueerders aan 'n vaste basis gekoppel is.

Die rekenaarbedryfstelsel bestaan uit vier dele:

1. **Simulasie**: 'n Rekenaarprogram is geskryf om die beweging van 'n vlak, Gough-Stewart-platform na te boots. Dit is gedoen deur die basiese beginsels van Newton-Euler-dinamika toe te pas op 'n meganiese model van die platform. Hierdie doelgerigte en toegewyde simulasieprogram stel 'n mens in staat om die *terugwaartse dinamiese analise* van 'n vlak Goug-Stewart-platform ekonomies te doen. Dit behels die gebruik van geslote-vorm wiskundige uitdrukkings waardeur die onbekende aktueerderkragte tydens die uitvoering van die *voorgeskrewe baan* bereken kan word. As deel van die terugwaarste dinamiese analise voer hierdie spesiale rekenaarprogram ook die terugwaartse kinematiese analise uit deur gebruik te maak van geslote-vorm uitdrukkings vir die posisies, snelhede en versnellings van die individuele liggame waaruit die masjien bestaan.

2. **Trajekbeplanning**: 'n Nuwe intepolerende *trajekbeplannings*-algoritme is ontwikkel waarmee die gebruiker die verlangde baan, wat deur enige *vlak* industrieële robot en gevolglik ook die vlak Gough-Stewart-platform gevolg moet word, analities kan spesifiseer. Met sekere voorgeskrewe kinematiese vereistes bekend, asook die gespesifiseerde node-punte langs die baan, pas die trajekbeplannings-algoritme interpolerende kubiese latfunksies in die tyddomein. Verdere insette van die gebruiker is egter nodig om te bepaal hoe die orientasie-hoek van die meganisme se beheerde eindwerktuig moet varieer langs die voorgeskrewe baan. Ten einde die aktueerderkragte langs verskillende voorgeskrewe bane te bereken, is die trajekbeplannings-algoritme gekombineer met bogenoemde terugwaartse dinamiese analise van die vlak Gough-Stewart-masjineringsplatform.
3. **Optimering**: Die lewensvatbaarheid van 'n vlak Gough-Stewart-platform met 'n *verstelbare geometrie*, lê daarin opgesluit dat dit moontlik is om die onbekende aktueerderkragte langs enige voorgeskrewe baan en op enige gegewe tydstip te bereken. Die rekenaarsimulasie van die meganisme stel 'n mens in staat stel om die werkingsgeometrie van die meganisme te *optimeer* na gelang van die voorgeskrewe baan. Die enkelmaatstafdoelfunksie wat hiervoor gebruik word, is die mimimering van die "maksimum-grootte-aktueerderkrag" wat via bogenoemde dinamiese rekenaarsimulasie geïdentifiseer word. Die minimering van hierdie doelfunksie, met betrekking tot die verstelbare geometrie, waarborg dat singuliere konfigurasies geassosieer met oneindige groot aktueerderkragte tydens die uitvoering van die voorgeskrewe baan, vermy word. Verder moet die minimering van hierdie doelfunksie uitgevoer word met inagneming van geformuleerde ongelykheidsbegrensings. Sodoende word die meganiese uitvoerbaarheid van die berekende oplossing tot die *begrensde optimeringsprobleem*, verseker.

   Sodra die optimale werkingsgeometrie bepaal is, word die fisiese herkonfigureerbare vlak Gough-Stewart-platform dienooreenkomstig verstel, ten einde die voorgeskrewe baan suksesvol uit te voer. Indien dit onmoontlik is om die voorgeskrewe baan te volg, moet die gebruiker 'n beredeneerde besluit maak. Die spesifieke numeriese optimerings-algoritme wat in hierdie studie gebruik word (LFOPC), bereken die beste moontlike kompromie-oplossing indien daar geen lewensvatbare ontwerp vir 'n voorgeskrewe baan bestaan nie. Die beste kompromie-oplossing dui aan watter ongelykheidsbegrensings oorskry is, en tot watter mate. Hierdie kompromie-oplossing is noodsaaklik om 'n beredeneerde besluit te maak aangaande die stuksgewyse uitvoering van die voorgeskrewe baan op 'n lewensvatbare en optimale wyse.
4. **Beheer**: Afgesien van die konfigurasie-optimering van die Gough-Stewart-platform na gelang van 'n gegewe taak, genereer die rekenaarbedryfstelsel ook die beheerkode wat nodig is vir die verlangde variasie in aktueerderbeenlengtes. Gevolglik is 'n paar verteenwoordigende masjineringsbane fisies uitgevoer met behulp van die toetsmodel.

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Praise the Lord!

TABLE OF CONTENTS