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専　　攻	システム工学専攻
学位論文題目	Modeling, control and optimization of tree-type robotic systems using exponential coordinates
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論文内容の要旨

1. Background and objectives

In recent years, an increasing number of tasks are being performed by robots, and we can observe an increase in the use of automated machines at working stations in the industry to complete various tasks. Although robots can complete tasks at very high speeds that cannot be achieved manually with a high level of precision, their main weakness resides in their lack of versatility. This gap is particularly apparent in the domain of object manipulation, where robots are limited to simple pick-and-place tasks or linear wielding. Although some progress has been made in recent years, for example, the use of robotic arms in factories, we can currently only mimic human behaviors for repetitive tasks. These tasks are becoming increasingly difficult, more varied, and we continue to seek better, more precise, and faster results from robots. These constraints suggest that we need more flexible tools and a more general approach to task-based optimization schemes for developing such robotic structures. In order to overcome current robots weakness, the field of robotic modeling, control, and optimization is the main vector of improvement.

2. Exponential parameters and Genetic algorithms

The main choices to develop tools for robotic modeling, control and optimization are the choice of parameters to represent the systems behavior and the optimization strategy to meet the design requirements. The most well-known parameters in robotic design are the Denavit-Hartemberg parameters, or DH parameters, which are the industry standards and widely used in the industry. However, the DH parameters possess several flaws limiting the design possibilities of the robots, and hinder their implementation into efficient optimization algorithms. Mainly, they are inter-dependant parameters, making them hard to handle in optimization schemes. Here, the exponential parameters seem to be a good fit since they are more flexible, independant, and possess elegant rules for derivations which make them perfect candidates for the derivation of equations of motions. Paired with the exponential parameters, Genetic Algorithms (GAs) have been chosen for the optimization process. GAs are well-known for the wide research space they can provide, and the binary coding aspect can be easily implemented using the afore-mentioned exponential parameters, allowing for a wide array of possible design consideration in an optimization process. In this thesis, we briefly introduce those concept in the first chapter.

3. Closed-form dynamics expression and control of tree-type systems

In the second chapter, we focus on the expansion and automatization of the modeling process involving the exponential parameters. To expand the exponential coordinates theory, we choose to derive equation of motion for robotic structures comprising branching paths in their kinematic chain. Those structures are called tree-type systems (Fig.1), and cover a large pan of the possible robotic designs achievable nowadays. To describe the kinematic path taken by such structures, we propose an additional parameter describing the system topology: the chain matrix. As we focus on the manipulation tasks performed by robots, we consider the situation of a tree-type manipulator system grasping and displacing an object. Using the exponential parameters and the chain matrix, we propose an automatized computation of the equations of motion (manipulator, object, constraints) for such systems, as well as control strategies adapted to the redundant nature of tree-type systems.

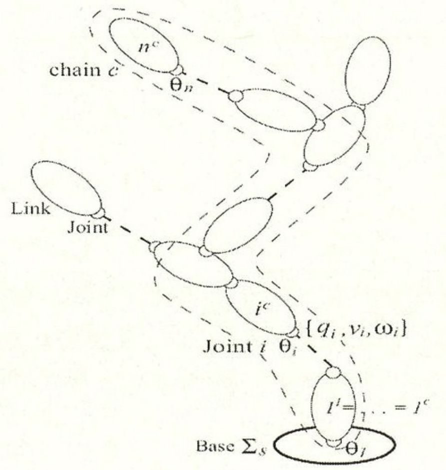

Fig.1 : Tree-type Systems

4. Binary adaptation for genetic algorithms and global design optimization

In the third chapter, we start by proposing a further extension of the exponential coordinates theories to sub-categories beyond tree-type systems: closed-chain systems, floating-base systems and platform systems. From there, we propose an algorithm to adapt the previously defined exponential parameters as well as the chain matrix to the genetic algorithms procedure, which allows for global or simultaneous geometry and topology optimization. To do so, we propose strategies to code those parameters into binary strings, which can then be optimized via the classic genetic algorithm scheme of reproduction, crossover and mutation operations. Additionally, we propose cost evaluations to rate the success of the proposed designs using feedback control of kinematics and dynamics in the proposed expression. The costs can be taken as the workspace volume, the total system mass or energy consumption, for example.

5. Simulation results

Using the proposed theories, after comparing the results with the standard general coordinate approach for a simple 2-D hand, we first simulate a well-known representative of tree-type robotic systems; an arm-hand system (Fig. 2), to prove the usefullness of the modeling and the control strategy incorporating redundancy. This scheme allows for a simultaneous control of the grasped object attitude as well as the system joint angles for examples, utilizing the remaining degrees of freedom allowed by the system architecture.

In the second example, we focus on the optimization of a platform system to increase its active workspace. Using the combination of exponential coordinates and GAs, we prove the simplicity and adaptability of the proposed method.

In the third example, an optimization of a modified version of the previously simulated arm-hand is proposed (Fig. 3). Here, we focus on a simultaneous optimization of the system geometry (represented by the exponential parameters) as well as the system topology (represented by the chain matrix) to minimize the total mass of the manipulator system, while completing a specific task.

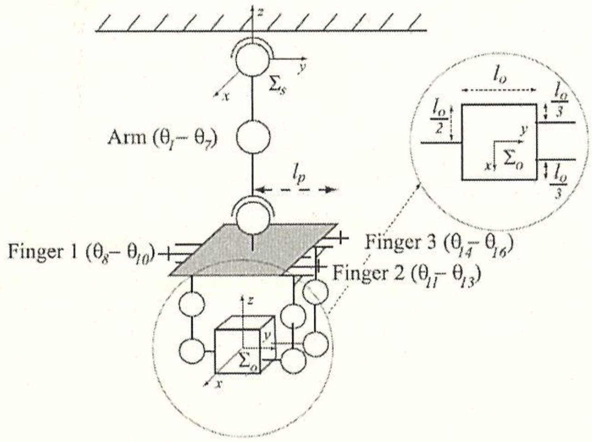

Fig. 2 : Arm-hand system

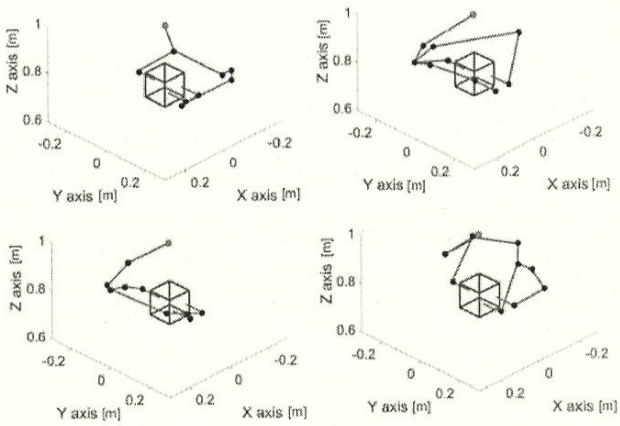

Fig. 3 : Observation of several optimization results

6. Conclusion

In conclusion, this thesis proposes a new modeling, control, and optimization method for robotic systems design. This method is based on a combination of exponential coordinates and GAs to allow for a very flexible modeling and automatized optimization process of robotic structures. This combination allow for a simultaneous geometry/topology optimization involving very flexible parameters, being able to scan a wide array of possible robotic designs which were difficult to implement until now. Some examples were observed to prove the usefullness of the proposed method.

論文審査の結果の要旨

本論文は，ジョイントとリンクが木の枝のように結合されて構成されているツリータイプシステム（ロボットシステムなどを抽象化したもの）に対し，指数座標を用いた運動モデル（運動学，動力学モデル）の構築方法と制御系の設計方法の提案（第 2 章），ならびに，その運動表現を用いたロボットシステムの位相構造と幾何構造の同時最適設計法の提案（第 3 章）を行っている．論文は，申請者が筆頭著者である 2 本のジャーナル論文に基づいて作成されている．

論文の内容は，広くジョイントで結合された多剛体系に対し適用可能なものであり，運動モデルの系統的かつ統一的な導出方法や，位相構造を含む大域的な最適構造設計の枠組みの提案は，博士論文に値すると判断した．また，予備審査において指摘された，軽微な記述の誤りや表現の曖昧さなどについても，適切に修正がなされていた．

最終試験の結果の要旨

令和 3 年 1 月 29 日にシステム工学部北 1 号館 A204 講義室において公聴会を実施した．公聴会では，45 分の発表の後，40 分の質疑応答を行った．発表は，論文の内容に基づき適切に行われていた．また，質疑においても適切な回答がなされていた．

以上の結果を総合的に判断し，学位申請者は博士の学位を授与するに値すると判断したため，最終試験は合格と判定する．