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研究課題名（英文）Analysis of geometrically constrained natural human movements and its application to robot control

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研究成果の概要（和文）：本研究では人間らしいリーチング運動を表現する数学モデルを構築する。先ずは人間上肢動作の数学モデルを確率的な定式化により構築した。具体的には確率的要素を仮定したうえで動作生成のための数理モデルを作成し、これを変分問題として扱うことで一種の最適制御問題として動作軌道を 求めた。次に、本研究の枠組みで、非ホロノミックシステムにおけるスムーズな動作生成の解析を行いました。非ホロノミック拘束の下での巧みな運動を理解するために、平面上に置かれた球の回転を利用した移動運動で、接触領域に制限がある場合についての運動計画に対して動力学的な解析を行った。提案した計画アルゴリズムは最適制御を用いた。

研究成果の概要（英文）：The research deals with mathematical modeling of human-like rest-to-rest reaching movements. Two models, the deterministic minimum effort model and the probabilistic minimum variance model, are under development and comparison. It was found that in the limiting case of post-movement time these models gives equivalent predictions under the assumption of the plant stability. The models were verified and tested under experiments using programmable haptic interface implementing a variety of holonomic constraints. Non-holonomic constraints were also addressed in the framework of this research. Here, reaching movements in the presence of rolling constraint were under investigation. A mathematical model of a spherical rolling robot was developed and the condition of dynamic realizability was established. Two motion planning algorithms have been proposed. A spherical rolling robot was designed and tested under experiment.

研究分野： 工学

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１．研究開始当初の背景

The study of natural reaching movement is very important in the design of control systems for modern skillful robots. Advanced robotic systems, designed for the physical interaction with human, are expected to play an important role in the future. The robots of the future will have the ability to predict and accommodate to human movements. To make this possible, we need to understand the basic principles of force-interactive constrained human motion and put them into quantitative models predicting human-like movements with reasonable accuracy. It seems likely that the human control system exploits fundamentally different control strategies for physically constrained and unconstrained movements. But how specifically do we deal with the external constraints, and how does the human control system resolve the actuation redundancy brought by the external constraints? The answers to these questions are very important for the construction of intelligent control systems for robot manipulators interacting with the external environments.

２．研究の目的

The main purpose of this research was to develop and experimentally verify control principles for the generation of human-like, rest-to-rest reaching movements in geometrically constrained dynamic environments. The principles are expressed in the computational mathematical models that can be transferred to the control system of real robots.

３．研究の方法

The project combined both the theoretical and the experimental parts. In the experimental part we have utilized a Phantom-based haptic interface and designed a simulator able to implement a large variety of the external holonomic constraints. When dealing with non-holonomic constrained we designed a spherical rolling robot actuated by internal rotors and tested it under experiments. In the theoretical part, we used the methods of analytical mechanics, optimal control theory and reinforcement learning control. The trajectory formation in both the motion and force domains was predicted by minimizing different criteria of optimality and compared against experimental data.

４．研究成果

In the first part of this research we dealt with modeling of human-like reaching movements in dynamic environments. A simple but not trivial example of reaching in a dynamic environment is the rest-to-rest manipulation of a multi-mass flexible object with the elimination of residual vibrations. This a complex, sport-like movement task where the hand velocity profiles can be quite different from the classical bell shape and may feature multiple phases. First, we established the beta function as a model of unconstrained reaching movements and analyze it properties. Based on this analysis, we constructed a model where the motion of the most distal link of the object is specified by the lowest order polynomial, which is not uncommon in the control literature. Our experimental results, however, do not support this model. To plan the motion of the system under consideration, we developed a generalized model that takes into account the dynamics of the flexible object and the weighted natural boundary conditions, minimizing square derivatives of the hand position over the movement time. It has been show that it gives a satisfactory prediction of human movements and explain the acceleration jumps at the beginning and the end of movements.

Next, we analyzed human-like reaching movement in stochastic formulation and constructed a continuous formulation of a probabilistic minimum variance model and compared with deterministic minimum effort model, describing and predicting the invariant features of the rest-to-rest reaching movements. The model features a parameter, having the meaning of the post-movement time period, whose assignment in a systematic way is not evident. To facilitate the situation and avoid the explicit specification of this parameter, the limiting case of the post-movement period tending to infinity is analyzed for several classes of the control plant. It has been shown that the in the limiting case these two different models, the minimum variance and the minimum control effort ones, predict the same outcome if the model of the control plant is stable. The theoretical models have been verified under experiments in virtual environments with the use of haptic interface and a simulator incorporating different holonomic constraints.

Finally, we also dealt with non-holonomic constraints. A typical, yet the most complex, example is represented by rolling. Here, we considered reaching movement for a rolling robot actuated either by internal rotors or a pendulum. This system is not differentially flat and not nilpotent and the conventional motion planning methods are not applicable. It was found that kinematically assigned motion trajectories may not be dynamically realizable and this requires the development of new techniques. It was established that the optimal control formulation produces the Euler's elasticae curves but the numerical implementation is sensitive to the initial guess and can be ill-conditioned. To alleviate these difficulties, a motion planning strategy employing a nilpotent approximation, iterative steering, and the geometric phase approach for the generation of control actions has been developed and verified under simulation. In addition, two spherical rolling robots, one actuated by internal rotors and one by pendulum, have been designed and their motion abilities have been verified under initial experiments.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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６．研究組織

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