Development of a Highiy Efficient Dynamics Simulator for Whole Body Motion Analysis of a Humanoid Robot(ヒューマノイドロボット全身運動解析のための高効率動力学シミュレータの開発)

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論文内容要旨

Chapter 1. Introduction

This thesis has two main goals; (1) to establish a high speed dynamics simulator of a humanoid robot, including the precise contact/friction model and the integrated balance compensation system, (2) to analyze the whole body cooperative motion for generating large Cartesian force, including optimization to yield automatically optimal posture corresponding to given the large Cartesian force.

The extended O(n) algorithm for forward dynamics of general open kinematic tree-structure chain is to be presented. This method is based on the efficient algorithm for calculation of forward dynamics in open serial chains developed by Rosenthal. It is basically similar to O(n) algorithm published so far in that application of recursive method in three passes; forward pass to construct the kinematics, backward pass to get the first dynamical equation, and final forward pass to the rest of the dynamical equations. However, a class of problems to which O(n) algorithm has not been applied so far is described by the situation where hyper multi-body system requires not only precise friction force but also rapid dynamics calculation changing by the external force. This happens, for example, when the humanoid robot equipped the simple and exact contact/friction model does walking or arbitrary tasks with surrounding circumstances. And it is represented physical phenomena such as slip and vibration, etc., corresponding to the friction force and ZMP. This contact model can be easily extended to other structures. There are variability and efficiency in the sense that this dynamics simulator is available for testing algorithm that have been explicitly designed to work in varying configurations, and for generating the motion pattern to maintain static or dynamic stability with high speed.

On the other hand, the ordinary researches have been only focused on stability of posture in the locomotive motion or simple works which are always restricted by the torque limit of arm's actuator. Especially, a few researches considering singularity using whole body cooperative motion for some work have been performed so far. From this point of view, this thesis is useful to the analysis of various whole body cooperative motions through stretching arm with adjacent singularity in accordance with axial direction. It also contributes to optimal posture of a humanoid robot to minimize joint torque over the entire model, including the evaluation of stability.

Chapter 2. Development of a High Speed Dynamics Simulator

In the development of the complicated and sophisticated robot like a humanoid robot, it is required to many complicated works such as setting of geometric parameter, construction of operating interface, analysis of dynamic characteristic, development of stable motion pattern algorithm for the human, and training of operator,

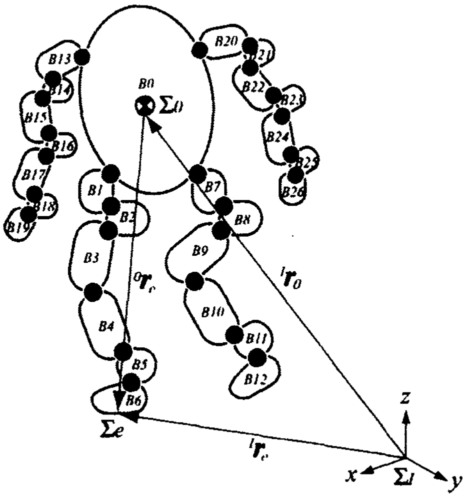

Fig.1: An articulated multi-body model of a humanoid robot.

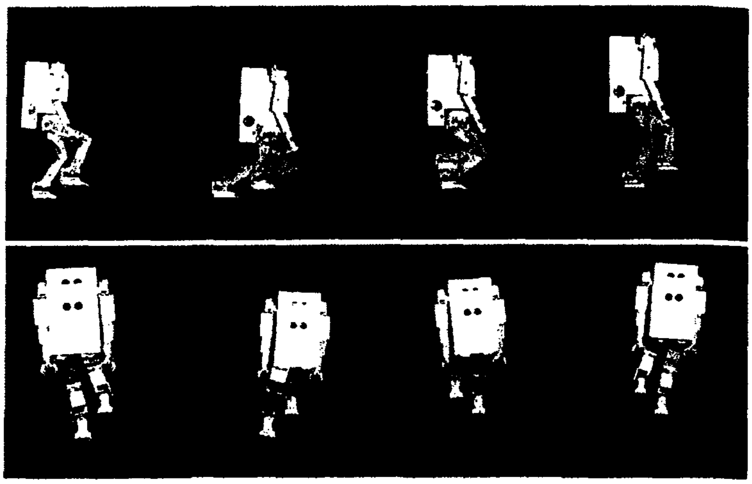

Fig. 2: Snapshots of simulation of ascending 20 [°] inclinations stairs (upper: side view, lower: rear view).

etc. Therefore, the dynamics simulator is indispensable one in efficient development of humanoid robot.

The Newton-Euler formulation requires O(n) arithmetic operation in the calculation of inverse dynamics, where n is the number of degrees of freedom of the system. On the other hand, a general solution method of forward dynamics is first to calculate each matrix element of the equation of motion using the method of the inverse dynamics, next to solve it with respect to angular acceleration, and finally to calculate velocity and angle of joint through integrating the angular acceleration of joint. In this process, the inertia matrix and its inverse matrix require $O(n^2)$, $O(n^3)$ arithmetic operations, respectively. O(n) algorithm for the high speed calculation of forward dynamics was first proposed by Featherstone in 1983. And then, several O(n) algorithms were proposed . The most efficient solution method among four solution ones proposed by Walker and Orin is $O(n^3)$, and it is more efficient than Featherstone's method, when n = 6. Therefore, if a system has about 6 degrees of freedom, advantage to apply O(n) algorithm becomes negligible. However, advantage of O(n) algorithm in the hyper redundant multi-body system like a humanoid robot becomes overwhelmingly. Using a parallel programming, arithmetic operation can be lowered even to O(log(n)).

In this research, based on Rosenthal's method of forward dynamics and Suzuki and Kojima's method, which is to improve Rosenthal's method as it can apply to a tree-structure and its equation of motion is described by Newton-Euler formulation, the high speed dynamics simulator has been developed. In order to calculate the ground reaction and friction forces, and to simulate slip to occurring when friction force exceeds its limit, the contact/collision model will be introduced by the virtual spring-damper model. In order to verify the developed dynamics simulator, a numerical model of a humanoid robot of 26 degrees of freedom is constructed (Fig. 1), and simulation of ascending stairs is carried out (Fig. 2).

Using the PC which has a CPU of Intel PentiumⅢ 866 [MHz], the execution time of simulation is 224 [s] for motion time 21 [s] by Euler's method at integration time step 0.1 [ms]. Accordingly, time required during the a loop is 1.067 [ms]. Supposing that execution time of CPU is proportional to the number of block, and computing the execution time of one degree of freedom in 1 [GHz] CPU, it becomes 0.0355 [ms]. It was described that execution time required during a loop by Yamane is 3.66 [ms] using the PC which has a CPU of Intel Pentium Ⅲ 1[GHz], when the dynamics calculation of 34 degrees of freedom of humanoid robot is carried out. Converting to the execution time per a degree of freedom, it is about 0.1076 [ms]. Even though the computational complexity cannot be completely compared because condition or function of simulation is different, it refers evaluation of developed simulator for the computational complexity.

Chapter 3. Inverse Kinematics and Trajectory Generation

This chapter discusses the inverse kinematics for the numerical model with redundancy and the stable trajectory generation with ZMP in dynamic walking motion. The inverse kinematics of each joint angle for the numerical model including the 7-DOF arm with redundancy is presented. To obtain solution of inverse kinematics for arm with redundancy, elbow position is calculated by the definition of the arm angle. From this, arm angle can be set appropriately by arm torque generated according to the characteristic of work or surrounding circumstance, etc. The trajectory generation of the stable dynamic walking motion pattern with ZMP is represented. The base motion to match foot trajectory should be always controlled inside the stable region. To minimize ground reaction force at foot landing, the quintic polynomials is used in the foot trajectory generation.

Chapter 4. Balance Compensating Method by ZMP Manipulation

Most of researches for the humanoid robot with the exception of its hardware development may be divided into two categories. One is motion pattern generation mentioned in previous chapter 3, and the other is balance control which is introduced in this chapter. In order to apply the developed humanoid robot to various works or motions which are intended by the operator, first of all, it is important to decrease error between the pre- and post-motion generated by the various factors such as gravity, inertia force, and external force, etc. In other words, this means that the integrated compensating control system is required to maintain the stability of robot and to accomplish the intended work under the various situations. In this chapter, four control methods for compensating balance are proposed and integrated as a control system. They consist of; (1) position compensating method of the COG by horizontal movement of trunk, (2) gravity compensating method of hip joint in support leg, (3) foot landing position compensating method of swing leg, (4) ankle joint torque compensating method of support leg. Each compensation method is integrated as a balance control system, and it is applied in dynamic walking motion to verify its efficiency. In the numerical example, the robot is regarded as a point mass with concentrated total mass on COG, it is carried out the balance compensation during the dynamics walking.

Chapter 5. Analysis for Whole Body Cooperative Motion

A human being often uses not only arm but also whole body to generate the efficient action force. Especially, the whole body cooperation is needed to accomplish some heavy works such as opening a heavy door and twisting a valve. In such work, if the static force is insufficient to accomplish a work, a human being would accumulate momentum by moving the body and make an impact to the environment. Accordingly, the human being can generate a large force which surpasses the maximum static friction force. Among the works, pushing a wall and twisting a valve are taken as examples of heavy works as shown in Fig. 3 and 4.

In this chapter, whole body cooperative motions of humanoid robot are discussed and tested various cases. One is cooperative whole body motions in ascending stairs, and the other is several patterns of whole body cooperation in two types of work which needs a large action force, such as pushing a wall and tightening a valve. These motion patterns to generate the efficient force for heavy works are studied, and static stabilities for the various postures of humanoid robot are evaluated. Static stability is evaluated through simulation results that include

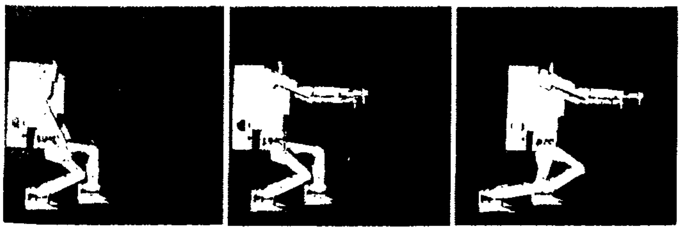

Fig.3: Snapshots of pushing a wall.

Fig. 4: Snapshots of twisting a valve.

external force, joint torques, position of the center of gravity and ZMP, etc. In the motion planning, these data are useful to evaluate the efficiency and stability of the motion.

Chapter 6. Optimization of Whole Body Cooperative Motion

Generally, a human tends to choose his posture, which is to be minimized the loads of his joints in order to avoid fatigue while doing some works. And a human also minimizes the loads of his joint and generates the maximum force by changing the posture of body, when he is doing some works requiring the large amount of force. All of these works for humanoid robot should not exceed the joint torque limit to avoid the damage on the actuators. In other words, range or area of work is restricted by the joint torque limit.

This chapter discussed the optimization technique for optimal posture of humanoid robot in generating large Cartesian force. An evaluation function of joint torque for entire model in the form of an object function was set, and the optimal posture minimized an evaluation function for the external force is selected by adjusting the end-effector and main-body in the sagittal plane. An object function is set to minimize torque for an entire model under the condition satisfying constraints and the required external force to be applied for whole body cooperative task can be met by adjusting the end-effector and main-body. Moreover, in order to maintain the stability of system during the optimization process, moment should be considered and applied to select the optimal posture. This approach contributes to the generation of the motion pattern and the determination of work range in practice. By using the optimal posture in some tasks, efficiency of work is increased and flexibility of selection of work is enlarged. In optimization, the accuracy of result and computational time depend upon the number of constraints, and proper setting of constrained condition of constraint.

Fig. 5: The configurations of optimization (left: pre-optimized configuration, right: post-optimized configuration).

Chapter 7. Conclusions

This thesis has presented development of dynamics simulator for a humanoid robot and its applications for the various situations. To grasping of dynamic characteristic of humanoid robot, therefore, is difficult. This dynamics simulator would serve as a tool for various purposes such as performing tests of a physical, testing dynamics algorithm, and generating motion pattern, etc. with highly efficient calculation of dynamics. The efficiency of computational complexity affects the basis of the real-time control of multi-body system. Specially, contact and friction model by the virtual spring-damper can represent the ground reaction force and friction force, etc. Accordingly, this approach can realize the accurate physical phenomena as closer as possible to the actual slip. Several whole body motions tested and verified to generate the large Cartesian force in arbitrary works. They would be served as the foundation for motion pattern generation to increase efficiency of work and to enlarge the work range of humanoid robot. However, stability and physical limit of robot should be considered under the condition of which a robot is in generating large Cartesian force. Therefore, an optimization, as a technique to search optimal posture satisfying this situation has been proposed. Even though setting the object function as the evaluation function may be changed according to the characteristics of motions, factor of joint torque is most direct and efficient one to characterize the various motions of a humanoid robot.

審査結果の要旨

ヒューマノイドロボットに代表される複雑かつ精巧な高機能ロボットの開発では、幾何パラメータの設定、操作インタフェースの構築、動特性の分析、動作アルゴリズム開発、オペレータの訓練など、多くの複雑な作業が必要とされる。このような作業を効率的に行うためには、動力学シミュレータが欠かせない。このような背景により、ヒューマノイドロボットの動力学シミュレータが開発されているが、演算速度が十分ではない、すべり現象が検討されていない、などの課題があった。これに対して本論文は、Rosenthalの順動力学解法を基に、衝突および摩擦モデルを導入し、高速なヒューマノイドロボットシミュレータを開発し、さらに、そのシミュレータを利用して、ヒューマノイドロボットの全身協調作業、作業最適姿勢解析を行ったもので、全編7章よりなる。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、ヒューマノイドロボットの高速動力学シミュレータの詳細について述べている。開発したシミュレータは、すべりを精度良く模擬することができ、かつ従来のシミュレータに比べ、大幅な計算速度の向上が実現されている。本シミュレータでは、種々の形態のロボットモデルを容易に構築でき、汎用性が高い。

第3章では、ヒューマノイドロボットの逆運動学問題と歩行パターン生成について述べている。

第4章では、ゼロモーメントポイント（ZMP）を制御することで、ヒューマノイドロボットの姿勢を安定化する手法を提案し、開発したシミュレータでその有効性を検証している。

第5章では、ヒューマノイドロボットの全身協調動作について、開発したシミュレータを用い、解析、検証している。急傾斜階段昇降、壁押し作業、バルブ回しの三つの作業を全身協調作業の例とし、どのような姿勢で作業を行うべきかを解析し、様々な姿勢、行動パターンでこれらの作業をシミュレーションし、解析結果と比較、検討している。すべりの考慮、運動量を利用した大きい力の発生など独創性が高く、かつ実機では危険で検証できないようなアイデアを数多く盛り込んだ行動パターンを提案しており、その意義は大きい。

第6章では、全身協調作業の例として、壁押し作業を取り上げ、線形計画法を用いて、大きい力を発生するための最適姿勢を求める手法を提案している。本章の結果は先駆的なものである。

第7章は結論である。

以上要するに本論文は、ロボットと環境との間の摩擦による拘束を考慮しつつ、Rosenthalの順動力学解法を基に、従来になく高速な動力学シミュレータを開発し、さらにそのシミュレータを用いて、ヒューマノイドロボットの全身協調作業、作業姿勢最適化の先駆的な研究を行ったもので、その成果はロボットシステム全般に適用可能で、機械工学およびロボット工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。