A Humanoid Robot Motion Generation Method to Perfom Tasks Utilizing Impact Dynamics(衝撃力を活用した作業実現のためのヒューマノイドロボット動作生成手法)

著者	辻田 哲平
号	53
学位授与番号	4086
URL	http://hdl.handle.net/10097/42500

氏名	つじた　てっぺい 辻田　哲平
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指導教員	東北大学准教授　近野　敦
論文審査委員	主査　東北大学教授　内山　勝　　東北大学教授　吉田　和哉 東北大学教授　小菅　一弘　　東北大学准教授　近野　敦

論文内容要旨

In order to exert a large force on the environment beyond limitation of actuators, it is effective to apply impulsive force. However, exerting impulsive force is one of the most dangerous tasks for a humanoid robot, since the generated reaction force may bring the humanoid robot down. Therefore, the main goal of this research is to develop a methodology to generate an optimal motion under stability constraint. We define a motion that performs a task by applying impulsive force as an ``impact motion." In this research, nailing task and punching motion are taken as an example of impact motion. This thesis has three contributions as follows.

The first contribution is experimental analysis and basic motion generation method of a nailing task. This research proposes a way to generate a pose at the time of impact with the joint velocities for humanoid robots to exert a large force and a robust feedback control method for driving a nail. The offline motion design method is not robust to error in the position of the nail since timing of pulling up a hammer is defined in the designed motion in advance. Therefore, a robust feedback control method for driving a nail is developed. The feedback controller stops execution of the motion generated offline when an impulsive force is detected by the force sensor mounted on the hand. Experimental results clearly show effectiveness of the developed method. In the experiment, the driving depth is drastically increased.

In order to predict impulse exerted on an object, an impulse prediction model is evaluated. Asada and Ogawa proposed the *virtual mass* for analyzing dynamic behavior of a manipulator arm and its end effector that interacts with the environment. This concept of the method is the projection of the robot's inertia to the contact point by using a jacobian matrix. The behavior of the robot during the impact phase is approximated by a point mass dynamics. The concept lowers computational cost of the contact dynamics of the manipulators fixed on the earth drastically. Thereafter, the model is used for predicting impulse exerted on a nail. The predicted impulses are larger than actual impulse exerted on the nail at all the trials. The conceivable causes of the error are as follows.

- Effects of the feedback control program for nailing task and a postural stabilizer for maintaining the body balance.

- Elasticity and backlash of the hammer's gripper.

The *virtual mass* model does not consider effects of a servo controller. The feedback controller pulls away the hammer when impulsive force is detected. Therefore, the impulse exerted on the target is lower than that of a motion without the feedback. The error increases in proportion to the impulse exerted. A stabilizer for walking is implemented in the system of the humanoid robot HRP-2. The detail of its algorithm is nondisclosed, however, basic concept of commonly-used stabilizers are based on position control of center of mass. When the robot is subjected to external forces, in order to avoid falling, the stabilizer accelerates speed of its center of mass toward direction of the fall. This results in the body moving in the direction of the fall. By this modification of motion during impact phase, force is not exerted to the nail sufficiently. The effect of stabilizer is particular to humanoid robots. The *virtual mass* is computed here on the assumption that the hammer and the hand are connected rigidly. In reality, the hammer is held by grip force between the palm and the finger. Hence, there is minor backlash between the hand and the hammer. Since the handle of the hammer is made of polyacetal resin and the shaft is made of wood, there is also elasticity between the collision point and the hand.

For nailing tasks, accuracy of the contact position is significant. Therefore, trajectories of the hammer are measured. The trajectory is captured by a motion capture system. Error between the reference and actual trajectories is increased in proportion to the robot's angular momentum. Since the error in the position of the hammer caused by joint angle deflection is minor, main cause must be deformation of the shock absorbers and slip at the sole of the feet. Therefore, it is significant to determine the appropriate angular momentum at the time of impact. Since derivative of momentum yields force or torque between soles and a floor, the impact motion must be designed under a certain momentum and angular momentum limitation for avoiding falling or accuracy of the task execution.

The nailing task experiment shows that primary impact is an important parameter for the nailing task. When the robot drives a nail into a hard wood, the impulse exerted by the primary impact can be predicted by dynamics between the hammerhead and the nail since the hammer shaft and handle have elasticity. After the primary impact, subsequent contacts are observed in the experiments. In order to detect fall, all the impact forces generated by the contacts subsequent including the primary impact must be estimated. It is indispensable to predict ZMP trajectory during the impact phase by using the estimated impulsive forces. However, the *virtual mass* model cannot predict ZMP trajectory. In addition, total time including the subsequent contact is about 30 (ms). The *virtual mass* method is intended for high frequency collision phenomenon like collision between rigid bodies. In this domain, effects of the servo stiffness and the online motion controller cannot be neglected. Though force control can control contact force when the contact time is long, the control cannot effectively respond to this level of frequency in general since the inertia of the humanoid robot is large. Therefore, a new dynamics computation method which can treat the in-between domain is proposed.

The second contribution is a high speed dynamics computation method. The computation method is proposed to estimate impulsive force. The computation cost of the proposed method is lower than full-featured dynamics computation method since the computation method only considers impact phase. Multibody dynamics and the effect of the servo stiffness to impulsive force are also considered in the proposed method. The approach achieves a balance between computation accuracy and speed.

In addition, the method can predict ZMP trajectory during the impact phase.

In order to estimate impulsive force accurately, a model which can consider the servo stiffness is required. Hence, a three dimensional contact dynamics model is proposed to estimate impulsive force and impulse in practical tasks. An approach to compute the force at low computation cost is proposed. In order to compute dynamics of a humanoid robot, dynamics computation methods for a fixed manipulator cannot be applied without modifications since there are problems particular to humanoid robots.

Some challenges of the impact motion by a humanoid robot are as follows.

- Falling caused by impulsive reaction force.
- Changing constraint conditions.
- A humanoid robot has many degrees of freedom.

In order to deal with changes in the constraint condition, a humanoid robot is expressed by a free-floating space robot model. Different constraint conditions are expressed in the model by adding extra weight to the robot's sole(s). The mass properties of its end effectors are varied depending on the constraint conditions. This scheme can be applied for various constraint conditions without reconstructing the structure description.

In order to reduce computation cost of the contact dynamics of the humanoid robot, a simplified dynamics computation method is proposed. The concept of this method is to simplify the dynamics equation on the following assumption specialized for collision phenomenon.

- The joints angles of the robot are taken as constant immediately before and after the impact.
- The changes of the joint velocities are discontinuous and cannot be ignored.
- The joint accelerations increase exponentially.

With these assumptions, jacobian matrix and inertia matrix can be regarded as constant values in the dynamics equation. Therefore, the computation cost is reduced since acceleration of the end effector can be obtained without computing the jacobian matrix and the inertia matrix at each simulation step. In this simulation process, the joint accelerations are computed. Hence, behavior of the links can be obtained and ZMP trajectory during the impact phase can be predicted. Since the *virtual mass* method does not compute the behavior of the links during impact phase, the model cannot compute ZMP trajectory.

In order to evaluate accuracy of estimation of impulsive force and ZMP trajectory, nine types of punching motions are designed heuristically. In addition, in order to see the accuracy of the *virtual mass* method, the impulsive force is estimated by using the *virtual mass* model. The estimation results of each motion are compared with simulation results by OpenHRP3. As an example, a contact model between the hand and the target is expressed by the commonly-used spring and damper model in the evaluation. This scheme is not dependent on the contact model and any contact model can be implemented. The maximum force errors are minor in both estimating method. The impulse error of the *virtual mass* method, however, is not negligible. The maximum error of the *virtual mass* method is about 116 (%). On the other hand, the impulse error of the proposed method is small. The maximum error is about 6 (%). Therefore, the proposed method is useful for estimating dynamics behavior of a humanoid robot. The trend of estimated ZMP trajectory by the simplified dynamics computation method is quite similar and the position error is under about 0.03 (m) in each direction. This method is applied to a proposed impact motion generation method.

The third contribution is an impact motion generation method. By using the proposed dynamics computation method, a force exerted on a target by a humanoid robot's whole body is maximized while maintaining stability. The motion is divided into acceleration, impact and slowdown phases. In all phases, stability is considered in the optimizing process. The dynamics computation method and the motion generation method are evaluated by performing a punching motion. The proposed method can generate a whole body motion utilizing impulsive force while maintaining stability. The motion is designed as follows.

1. Determining end effector's velocity, momentum, angular momentum and CoM (Center of Mass) velocity at the time of impact.
2. Interpolating these physical values from zero and to zero.
3. Generating motions for acceleration and slowdown phases to satisfy the interpolated trajectories.

With this scheme, stability during the acceleration and slowdown phases can be evaluated in the optimizing process without computing inverse dynamics. This is an important concept of the proposed method.

Stability during the whole motion is evaluated by two methods in the optimization process. The stability during the acceleration and slowdown phase can be evaluated with the above-mentioned scheme. The stability during the impact phase can be evaluated by the proposed simplified dynamics computation method. In order to maximize the generated impulsive force, the contact dynamics simulation is repeated a number of times in the optimization process. The simplified dynamics computation method can produce a solution faster than the full-featured one. With the optimal end effector's velocity, momentum, angular momentum and CoM velocity, reference trajectories of the acceleration and slowdown motions are generated by third-order polynomial interpolation.

These contributions are implemented to an impact motion generating software. The software is developed by using the technical computing language MATLAB R2007b (The MathWorks, Inc.).

論文審査結果の要旨

ヒューマノイドロボットは人間を模した形状のロボットで，人間のために整備されたインフラを活用できるため，人間との共同作業や福祉，介護の分野への応用が期待され，これまで多くの研究が行われてきた。しかし，ヒューマノイドロボットを駆動するモータは，単位質量あたりの出力が，人間の筋肉と比較すると１～２桁ほど小さい。このため，人間が行う力作業をヒューマノイドロボットに行わせることは，困難な場合が少なくない。

本論文は，以上の問題を解決するために，衝撃力を活用して，ヒューマノイドロボットに大きな力が必要な作業を行わせることを提案し，そのような動作の生成手法を議論したもので，全編６章からなる。

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，衝撃力を活用したヒューマノイドロボットの動作（インパクト動作）生成を支援するために開発したソフトウェアについて述べている。開発したソフトウェアは，衝撃力印加時に環境から受ける反力や，姿勢安定性の指標となるゼロモーメント点をグラフィック表示することができるため，インパクト動作の生成と実験結果の解析が容易になる。このソフトウェアを用いてヒューマノイドロボットの釘打ち動作を生成し，実験結果の解析を行っている。このようなインパクト動作生成・解析ソフトウェアは，ヒューマノイドロボットの動作生成に必要不可欠なもので，この成果は非常に重要である。

第３章では，第２章の解析結果を基に，最適化の手法を用いてインパクト動作を生成する手法について述べている。第２章で述べている動作生成・解析ソフトウェアにより，インパクト動作の生成が劇的に容易になるが，人間の手で生成した動作は，必ずしも最適な動作になるとは限らない。本章の手法により，目的関数を最小化する最適なインパクト動作を自動的に生成できるようになる。例として釘打ち動作を生成し，実験を行い，実用的な作業における衝突現象の周波数解析を行っている。この成果は非常に重要である。

第４章では，新しい衝突動力学簡易計算法を提案している。衝突前後のロボットの転倒を回避し姿勢安定性を保証するには，ロボットが環境に衝突する前後の区間で衝突の動力学計算を繰り返し，その結果を基に第３章で述べた最適化手法を用いて最適な動作を探索する必要があるが，この動力学計算が高速に実現できなくては，動作生成に膨大な時間を必要とし，実用的ではない。この問題を解決するために，第３章での周波数解析を基に，十分な精度を保ちつつ従来の手法に比べて劇的な高速化を実現する，衝突動力学簡易計算法を提案している。この成果は有用で重要なものである。

第５章では，第３章，第４章での成果を踏まえ，衝突時の姿勢安定性を保証する，一般的なインパクト動作生成のための手法を提案している。この手法は，大きな力が必要な一般的な作業に応用でき，ヒューマノイドロボットの実用性を大いに高めるものである。この成果は，ヒューマノイドロボットの実作業への応用に向け，非常に重要なものである。

第６章は結論である。

以上要するに本論文は，環境との衝突を伴う作業をヒューマノイドロボットに行わせるために，衝突時の姿勢安定を保証しつつ衝突力をできるだけ大きくするような動作生成手法を提案し，シミュレーションと実験でその有効性を確認したもので，提案された動作生成手法の応用性，汎用性を考慮すると，航空宇宙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。