Advantages of Singular Configurations in Robot Motion

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論文内容の要旨

氏　名　万象隆

専　攻　システム科学

論文題目（外国語の場合は，その和訳を併記すること。）

Advantages of Singular Configurations in Robot Motion

(ロボット動作における特異姿勢の有用性)

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（注）2，000字～4，000字でまとめること。

Human beings can dexterously perform highly dynamic motions. For instance, we achieve efficient walk by utilizing the posture with extended knees and hips. We push or pull a heavy object as a habitual and physically strenuous task. When we pull an extremely heavy object, we use our whole bodies. The translational momentum (or kinetic energy) of the trunk is generated before we apply a pulling force to the object with our hands, and then a large force is applied to the object near a configuration where the arm is fully extended. Human beings usually lift up heavy objects to a higher place in the daily life. In a weight lifting motion, an athlete lifts up a heavy barbell. He or she firstly extends his robot manipulators and then suddenly starts to lift it from the ground. After lifting it above his head, the body stretches to sustain the barbell. In a vertical jumping motion of human beings, the leg stretches rapidly in an aligned position in stance phase, and the take-off posture is almost stretched out. In these motions, the extended postures of human beings, that are called singular configurations in robotics, seem to be very useful. As we know, both human beings and robots can be modeled as multibody systems, and they have much in common.

The development of the robots that can perform human-like movements has attracted many researchers. Over the past decades, researchers have proposed several robot manipulators to perform highly dynamic tasks such as grasping, batting and throwing by their end-effectors. The lifting motion performed by the robots in behalf of us has been studied well.

Mobile manipulators are expected to perform various tasks by using the manipulator mounted on the mobile platform. Due to fukushima daiichi nuclear disaster, the mobile manipulators that can work in unknown and dangerous environment instead of human beings attract the interest of many researchers recently. Mobile manipulators have been used inside the fukushima daiichi reactor buildings for several purposes such as opening door and picking up debris.

Many of the robot manipulators (including the mobile ones) are equipped with the actuators with high performance. However, powerful actuators often have heavy weight, and may bring external energy consumption during robot motions, especially by the mobile robots which are powered by the batteries. When these mobile robots work in an unknown environment such as an earthquake rubble or a nuclear rubble, there would be adequate power supply for any emergency issue. If the tasks are performed efficiently even by small actuators, energy consumption can be reduced and the tasks can be achieved as much as possible before running out of batteries. Therefore, there is a pressing need to find a way of efficiently achieving dynamic tasks.

In robotics, a robot configuration that has a degenerated Jacobian matrix is called singular configuration. The kinematic properties of singular configurations are well-studied. In a singular configuration, the robot end-effector loses one or more degrees of freedom, and cannot be freely controlled in each direction. For this reason, many control and motion planning strategies have been used to avoid the singularities. Nevertheless, the control and motion-planning process becomes more complex and the range of feasible tasks is restricted.

As we know, everything has two sides. Some researches showed that singular configurations are also advantageous in several robot motions, even though the advantage has been neglected for a long time. As mentioned earlier, human beings dexterously utilize the singular configurations in several motions such as walking and pulling. When we make the robots perform such dynamic tasks like human beings, it becomes necessary to understand the dynamic features of robot near their singular configurations. This dissertation focuses on the relation between the robot motion and the singular configurations.

Chapter 1 introduces the background, motivation and goal of this dissertation.

Chapter 2 derives the kinematic and dynamic equations of a multibody system as a general representation. Since this dissertation deals with several kinds of robots, the corresponding kinematics and dynamics can be easily calculated based on the obtained equations.

Chapter 3 lists all the features of singular configurations observed up to now. Two of them have been noticed but not theoretically explained before. A simplified model of a two-link manipulator is considered, and the two features are verified through theoretical analysis. The main contribution is that this dissertation provides a theoretical explanation on the dynamic features of singular configurations, which can be utilized in robot motion.

Chapter 4 deals with the motions of two-link robot manipulators such as a manipulator with fixed base and a mobile manipulator with unfixed base. Sections 4.2 and 4.3 present the lifting motions of a 2-link robot manipulator, a lifting motion and a weight lifting motion, respectively. A heavy object attached to the end-effector is to be moved upward by the manipulator. In the lifting motion, the heavy object is lifted up a certain height from the lowest position, while the heavy object is lifted up to the highest position in the weight lifting motion. These motions are optimized for minimizing the necessary joint torques. The numerical simulation results show that the features of singular configurations are advantageous in generating energy, causing large acceleration, and reducing joint torques. Section 4.4 deals with the optimal motion of a mobile manipulator for dragging a heavy object with the end-effector. When the object is moved a certain distance, the torques that are consumed in the mobile manipulator during the motion are minimized by numerical optimization. In the optimized motion, the arm mounted on the mobile base passes through its singular configuration, and a large force to pull the object is generated simultaneously. A theoretical analysis is performed to explain the numerical results by using a simplified model of the mobile manipulator.

Chapter 5 deals with the motions of legged robots, including a two-link legged robot and a four-link legged one. Sections 5.2 and 5.3 obtain optimal jumping motions of a two-link legged robot and a four-link legged one. For the two-link robot, the robot motion in stance phase is considered, and a fixed amount of translational energy is supplied to the robot from joint torques by

the take-off time when the foot leaves the ground. For the four-link robot, the robot motion in aerial phase in addition to the one in stance phase is also considered, and the rotations of joints are stopped in the air by the time when the robot reaches the maximum height with the joints fully extended. For both the two-link robot and four-link one, the numerical optimization results show that the take-off posture that is close to a singular configuration has the advantage in supplying a large force (or acceleration) efficiently in stance phase. Furthermore, the numerical optimization results of the the four-link robot with different take-off postures show that the take-off posture close to a singular configuration is also useful for reducing the rotational energy that has to be eliminated in aerial phase. Even though the model of the four-link robot is more complex, the features of singular configurations can be noticed in the motions of both robots. Section 5.4 deals with optimal landing motions of a four-link legged robot that minimizes the impact force at the contact point and the joint torques necessary during the motion. The cost function for optimization is given as the weighted sum of the impact force and the joint torques. The configuration of the robot that is close to a singular configuration is advantageous in minimizing the joint torques for a heavy body, while the configuration where the leg is bent is advantageous in reducing the impact force. This is shown by numerical optimization results with different weights for the cost function and a theoretical analysis of a simplified model for the legged robot.

Finally, this dissertation is summarized in Chapter 6.

（別紙１）

論文審査の結果の要旨

氏名	万 象隆
論文題目	Advantages of Singular Configurations in Robot Motion （ ロボット動作における特異姿勢の有用性 ）

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要旨

ロボットアームの手先が伸びきった状態では手先速度を自由に指定できないように，ロボットには特異姿勢というものがあり，ロボットの手先の運動計画などにおいて特異姿勢が避けられてきた．しかし，本論文は動力学的視点から特異姿勢の特性を数値的，理論的に考察し，ロボット動作における特異姿勢の有用性について論じているものである．

まず，第２章で基礎となる n リンクシステムの運動学的および動力学的運動方程式をあげている．そして，第３章で，２リンクマニピュレータを例に特異姿勢の性質として次の４つをあげている．a) 特異姿勢付近では少ない関節トルクで大きな手先負荷に耐えることができる，b) 特異姿勢付近では関節の駆動トルクから効率的に力学的エネルギーを生成することが可能である，c) 特異姿勢付近では力学的エネルギーから大きな手先加速度を生成可能である，d) 特異姿勢付近で，関節の駆動トルクから大きな手先加速度を生成することが可能である．性質 a)および b)は既に示されていることであるが，本論文では性質 c)と d)を理論的に検証している．

第４章では，２リンクロボットマニピュレータの持ち上げ動作と，２リンクモバイルマニピュレータの引っ張り動作を対象とし，それぞれの動作時の消費トルクを最小にする最適化問題を考えている．数値最適化によって最適な運動を求め，得られた最適な動作においては，特異姿勢を通ることによって，前述の特異姿勢の性質を利用していることを示している．さらに，簡単化した等長リンクのモバイルモデルを用いてそれを解析的に説明している．

第５章では，２リンクおよび４リンク脚型ロボットを対象に，跳躍動作における消費トルクを最小にする最適化問題，そして，着地動作において着地時の消費トルクおよび衝撃力を最小にする最適化問題を対象に特異姿勢の有用性を考察している．まず，跳躍問題においては，数値最適化によって最適な運動を求め，二つの初期姿勢を比較した結果，求められた最適な動作において，特異姿勢に近い初期姿勢から始めた場合，特異姿勢の性質を利用して跳躍に必要なトルクを軽減できることを示している．次に，着地問題では，数値最適化によって最適な運動を求め，特異姿勢に近い姿勢からの着地で，特異姿勢の性質を利用して関節トルクを小さくできることを示している．さらに，簡単化したモデルにおいて衝撃を考慮して問題を定式化し，これを解析的に説明している．

以上，本研究は，ロボットの持ち上げ，引っ張り，跳躍，着地という４動作を対象として，それぞれの動作時の消費トルクを最小にする運動最適化問題の数値的，理論的考察を通してロボットの特異姿勢の有用性を動力学的に示したものであり，ロボティクス分野においてロボットの動作について重要な知見を得たものとして価値ある集積である．提出された論文はシステム情報学研究科学位論文評価基準を満たしており，学位申請者の万 象隆は，博士 （工学） の学位を得る資格があると認める．

- 特記事項
- 特許登録数 件
- 発表論文数 3 編