論文の内容の要旨

論文題目　Simultaneous Body Reconfiguration and Nonholonomic Attitude Reorientation of Free-flying Space Robots
（フリーフライング宇宙ロボットの形態再構成と非ホロノミックな姿勢変更の同時実現）

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In recent years, a number of space robot/spacecraft missions such as on-orbit construction, on-orbit refueling, and debris removal have been proposed. For such advanced space missions, future free-flying robots are expected to have more versatility, adaptability, and dexterity. One promising solution to the future demand is free-flying space robots with highly redundant actuatable joints Such a redundant robot can be adaptive and versatile by morphing into various structure on-orbit and can be dexterous using multiple manipulators simultaneously. However, when a space robot reconfigures its structure, its final attitude depends on its body reconfiguration procedure due to nonholonomy. Motion planning in nonholonomic system is difficult because it is proved that any time-invariant continuous feedback control is impossible to stabilize the system. Therefore, there is no general solution to the inverse problem of obtaining the body reconfiguration procedure that achieves arbitrary body configuration and attitude simultaneously.

Many researchers investigated the attitude dynamics of the free-flying space robots, but most of them only dealt with simple systems such as planar-restricted systems and a canonical chained/power system. Therefore, little research has been done to construct a motion planning method that can handle general robot models and general three-dimensional rotation.

The purpose of this study is to construct a simultaneous body reconfiguration and attitude reorientation method that is applicable to arbitrary free-flying robots without angular momentum, which is named as nonholonomic reorienting transformation, or NRT by the author. In order to derive the widely applicable control law, a kinematics equation that preserves Lie-group structure is adopted to describe the attitude motion. Owing to its mathematical structure, the attitude motion is analytically expressed with the Magnus expansion, and some of them are approximately integrable. In particular, a rectilinear solution is focused on, in which joints are actuated along a rectilinear path in joint angle space. This rectilinear solution is simple but powerful tool for motion planning and induces two different types of motion planning methods: 1) rectilinear transformation planning, and 2) rectilinear invariant manifold method. The former method generates consecutive rectilinear path in joint angle space whereas the latter method asymptotically attracts the state to a fiber bundle of invariant manifold growing from the target state. Numerical simulations for both methods demonstrated that body reconfiguration and attitude reorientation is accomplished regardless of model of the robot and dimension of the motion.

In addition, singularity analysis is provided for both methods. The analysis is discussed by analogy with control moment gyros and robotic manipulators, and an effective singularity-robust steering method is imported to the proposed methods.

Finally, as an example of practical applications, an orbital station keeping with a transformable solar sail is presented. The constructed NRT maneuvers enable the solar sail to change its equilibrium attitude and to reorient to the equilibrium attitude simultaneously, which greatly enhances solar sailing ability. As a promising example of orbits, an artificial small-amplitude periodic orbit around SEL1/L2 is designed. The designed artificial orbit is an ideal platform that provides stationary thermal/geometrical environment, whereas the entire orbit and attitude maneuver do not consume any propellant.

The ability to simultaneously achieve a target body configuration and attitude means that geometry of all body components of the free-flying space robot can be arbitrarily reconfigured, which contributes to various applications. Therefore, the motion planning methods developed in this study are expected to be a fundamental technology for advanced future space robot missions.