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授与した学位	博　士
専攻分野の名称	工　学
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学位授与の要件	自然科学研究科　産業創成工学専攻 （学位規則第５条第１項該当）
学位論文の題目	Underactuated Control for an Autonomous Underwater Vehicle with Four Thrusters （4つのスラスタを持つ自律水中移動体の劣駆動制御）
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学位論文内容の要旨

Chapter 1 overviews the nonlinear control problem, nonholonomic systems, underactuated mechanical systems, the factors that were driven to the research of underactuated system and the necessity of a condition for stabilizability of nonlinear systems.

Chapter 2 introduces fundamental ideas and concept regarding underwater vehicles, their design and control methods. The major design aspects that need to be considered are identifying hull design, propulsion, submerging and electric power. Another important things that require consideration for the design process are factors that affect an underwater vehicle such as buoyancy, hydrodynamic damping, Coriolis and added mass. AUVs present a challenging control problem because most of them are underactuated, i.e., they have fewer number of inputs than that of DOFs. Such control configurations impose non-integrable acceleration constraints. Furthermore, AUVs' kinematic and dynamical models are highly nonlinear and coupled, hydrodynamics of the vehicle are poorly known and may vary with relative vehicle velocity to fluid motion, and a variety of unmeasurable disturbances by ocean currents, making control design a difficult task. Therefore, appropriate nonholonomic or underactuated control methods are applied for this vehicle.

Chapter 3 describes the notation and coordinate systems, and introduces an explanation of the kinematic model and the derivation of a dynamical model of an X4-AUV. These equations are used in later chapters for controlling purpose. X4-AUV is designed with an ellipsoid body hull shape to minimize the drag forces acting on the hull while the X4-AUV is cruising. It is also equipped with four thrusters, has 6-DOFs in motion, falls in an underactuated system and also has nonholonomic features. The dynamic model of an X4-AUV is derived using Lagrange approach, with the assumption of balance between buoyancy and gravity. The modelling includes the consideration of the effect of added mass and inertia.

Chapter 4 presents a nonholonomic control method for stabilizing an X4-AUV. In this chapter, the x-, y-, and z-positions and angles of the X4-AUV is stabilized by using control inputs u_1, u_2, u_3, and u_4 respectively. PD feedback control law is applied to control the attitude and positions of the X4-AUV with the direct use of the Lyapunov stability theory. The stability of the system is ensured by the Lyapunov theorem and LaSalle invariance theorem. By the Lyapunov theorem, simple stability for equilibrium is ensured, whereas by the LaSalle invariance theorem, we can ensure an asymptotical stability starting from a point in a set around the equilibrium. In our case, this theorem ensures the global stability of the system. Note that the simulations for stabilizing the X4-AUV in the x-, y-, and z-positions are implemented independently.

Chapter 5 deals with a discontinuous control law for stabilizing an X4-AUV. The system is written in a control-affine form by applying a partial linearization technique. A dynamic controller based on Astolfi's discontinuous control is derived to stabilize all states of the system to the desired equilibrium point exponentially. Two approaches are applied to the system. The first approach does not necessitate any conversion of the system model into a canonical form while for the second approach, the system is converted into a chained form. The discontinuous dynamic-model without using a chained form transformation in the first approach assures only a local stability (or controllability) of the dynamics based control system whereas in the second approach, the discontinuous dynamic-model using a chained form transformation guarantees a global stability of the system. Assumption made in the simulation for the first approach is that the value of θ- and ψ-angles is very close to zero.

Chapter 6 gives a summary of this study and possible future enhancements concluded in this chapter.

論文審査結果の要旨

近年，水中移動体，取り分け自律水中移動体（Autonomous Underwater Vehicle）あるいはロボットの研究・開発は，水質調査，水中生物調査，海洋資源探査などのため重要視されつつある。従来の大型AUVでは操舵翼を利用することで操作性の向上を図ってきた。これに対して，操舵翼の効果があまり期待できない小型の AUV では，操作性を上げるにはスラスタの効果的な配置あるいは利用法と制御技術が 1 つのポイントとなる。

本研究では，4 つのスラスタを前進方向と垂直な平面内に等間隔で配置する X4-AUV に着目し，その力学モデルに基づく非ホロノミック制御法および幾つかの劣駆動制御法について提案した。

まず，従来の球状の機体は抵抗が大きいことから本研究では楕円型の機体に対する流体による付加質量や慣性モーメントを考慮した動力学モデルを導出した。このとき，4 つの入力により 3 つの姿勢と x あるいは y あるいは z のうちの 1 つの位置制御ができるリアプノフの安定理論に基づく非ホロノミック制御法を提案した。

次に，部分線形化法を導入した不連続制御について，2 つの方法を示した。1 つはロール角とピッチ角が小さいと仮定し，標準化モデルを利用しないで 4 入力 6 一般化座標の局所安定を保証する劣駆動制御を，もうひとつはチェインドフォーム変換を利用し 4 入力 5 一般化座標の大域安定を保証する部分劣駆動制御を提案し，それぞれの有用性はシミュレーションにて検証した。

このように本研究は自律水中移動体の一種である X4-AUV において，水中での抵抗の少ない楕円型機体の提案と，その動力学モデルに基づく非ホロノミック制御法と劣駆動制御を実現する幾つかの不連続制御法を示したものである。これらの成果はロボット工学，特に非ホロノミック移動ロボットの劣駆動制御技術の発展に寄与するものである。

本学位審査委員会は，学位論文の内容ならびに参考論文等を総合的に判断し，博士（工学）の学位に値するものと判断する。