Graduate School of Advanced Science and Engineering
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博　士　論　文　概　要
Doctoral Thesis Synopsis

論　文　題　目
Thesis Theme

Locomotion Performance of Autonomous Mobile Robot on Rough Terrain for Outdoor Survey
屋外調査用自律移動型ロボットの不整地移動性能

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Interest in field robots has been increasing since the radiation accident at the Fukushima nuclear plant due to the Great East Japan Earthquake in 2011. Field robots play a very important role as a means to protect human safety and discover new things. Mobile robots used for monitoring increase understanding of the environment and ecosystem to ensure better protection. Mobile robots are expected to solve problems of conventional monitoring methods such as monitoring posts, manual transport, bio-logging, and monitoring cars by reducing human labor costs and improving human safety and flexibility through microscopic monitoring.

The locomotion performance is one of the most important research subjects for mobile robots. Previous studies have focused on moving on rough terrain, and such robots are effective for a given target area and purpose. However, almost all of the robots with a high locomotion performance have many actuators to cope with complex environments. This leads to a complex robot design and high power consumption. These factors reduce maintainability and increase control complexity. In addition, many studies on controlling mobile robots use geometry sensors such as cameras and lasers in order to recognize obstacles and know the robot's position. This also leads to high computational cost and power consumption. In order to overcome these problems, the author focused on locomotion with a minimum number of actuators and autonomous movement using only simple sensors.

The objective of this study was to design a mobile robot platform with a high locomotion performance on rough terrain that has a simple design and low power consumption as a first step towards developing a large-scale and long-term monitoring system. The author proposes a method for a simple design and low power consumption by reducing the number of actuators and proposes a novel mechanical and control design to realize a high locomotion performance. In order to realize these concepts, the author set two design requirements: locomotion performance on rough terrain with a minimum number of actuators and outdoor navigation by simple sensors. Compared to other unmanned ground vehicle-type robots, the proposed robot is effective for long-term operation with reduced energy consumption and improved maintainability. The simple design can greatly reduce the unit cost, which can help with realizing the production of multiple robots for large-scale monitoring.

Chapter 2 introduces novel mechanical designs that help increase the locomotion performance with simplicity and low power consumption. Three important elements for designing a target robot are introduced: the locomotion mechanism, wheel shapes, and a shell shape. A novel locomotion mechanism using a driving mechanism that can drive multiple axes at once is introduced first. Then two novel wheel models are presented that can adapt to locomotion on rough terrain: an elliptic leg and notched wheel. Finally, a novel shell shape of the robot is introduced that can also contribute to a high locomotion performance, especially in areas thick with tall grasses.

Chapter 3 introduces a novel control design to increase the locomotion performance with simplicity and low power consumption. Three important elements of autonomous control design are introduced: environmental recognition, motion control, and navigation. A novel method of estimating surface conditions is presented to recognize the environment, and the possibility of acquiring details on the mobile environment with only internal sensors is discussed. A novel motion control design based on the subsumption architecture proposed by Rodney Brooks is then presented to realize autonomous control using only simple sensors. A navigation method is presented at the end of the chapter for efficient movement to get to the destination. Novel methods of generating a cost map and the selected path planning method are described as parts of the navigation method.

Chapter 4 introduces some application examples using the developed mobile robot. Experiments were conducted in various environments, and the elemental technologies introduced in Chapters 2 and 3 were used in combination. Monitoring in an urban park was conducted with the objective of image acquisition, and the camera on a smartphone with an omnidirectional lens was used to take pictures. Monitoring in a pasture was conducted with the objective of monitoring the radiation level. A Geiger counter was used for measurement. Monitoring in a forest was conducted with the objective of measuring geometric data. A laser range finder system was used. Another example application was tunnel and ceiling inspection. This example was in response to new demands originating from the small size and light weight of the robot.

Chapter 5 presents the overall discussion. The effect and validity of the proposed methods are discussed from the viewpoint of monitoring and locomotion performance. Then, the originality and impact of the proposed methods are considered. The main features of this proposal are described: the mechanism using only two motors and the control using only internal sensors. Finally, the limitations of the proposal are described: the limit of utilizing static mechanics as a model, the limit at which the energy efficiency is not optimized depending on the application, and the limit of the application range.

Chapter 6 describes the conclusions based on this proposal and details of plans for future studies.

To increase the locomotion performance of an autonomous mobile robot for monitoring on uneven terrain, this thesis proposes a novel mechanical design that uses only two actuators and a novel control method that uses only internal sensors based on the concept of a simple design and low power consumption. The effectiveness and validity of the methods were evaluated through verification experiments and application demonstrations.

The results showed that the mechanical shape of the part where the robot contacts the outside world is important, and a new wheel shape and casing shape are proposed. The importance of recognizing the surface with internal sensors is described, and methods of motion control that can adapt to the real environment and path planning using locomotion data are proposed. Examples of various applications using robots developed on the basis of these designs are presented, and their practicality and potential application are discussed and demonstrated.

The significance of the thesis is that it not only proposes a novel design to increase the locomotion performance but also describes the effects by introducing a generalized model and analysis from experimental data. Such descriptions will contribute to the design of other mobile robots to adapt to the target environment and help with selecting design parameters. The proposed design is simple and has low power consumption, which will contribute to reducing the manufacturing cost and the long-term goal of a monitoring system using multiple robots.

The results of this study can contribute to the further popularization of robots used outdoors and are expected to become the basic technology for future robot development owing to their generality and high potential applicability. Further developments based on this study will involve establishing a novel method of environmental monitoring. The study contributes not only to robotics but also to developments in the fields of environment and ecology. This can lead to great strides towards building a society where human beings coexist with nature in the future.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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種 類 別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
a. Academic papers ○	1. K. Tanaka, Y. Okamoto, H. Ishii, D. Kurowa, H. Yokoyama, S. Inoue, S. Okabayashi, Q. Shi, Y. Sugahara and A. Takanishi, “A study on path planning for small mobile robot to move in forest area”, *Proc. 2017 IEEE International conference on robotics and biomimetics*, December 2017. (記載決定)
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	3. K. Tanaka, D. Zhang, S. Inoue, R. Kasai, H. Yokoyama, K. Shindo, K. Matsuhiro, S. Marumoto, H. Ishii and A. Takanishi, “A design of a small mobile robot with a hybrid locomotion mechanism of wheels and multi-rotors”, *Proc. 2017 IEEE International Conference on Mechatronics and Automation*, pp. 1503-1508, August 2017.
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(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

種 類 別 By Type	題名、 発表・発行掲載誌名、 発表・発行年月、 連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
○	9. K. Tanaka, H. Ishii, D. Endo, J. Mitsuzuka, D. Kuroiwa, Y. Okamoto, Y. Miura, Q. Shi, S. Okabayashi, Y. Sugahara and A. Takanishi, "A Study of Wheel Shape for Increasing Climbing Ability of Slopes and Steps", *Proc. 21st CISM IFToMM Symposium on Robot Design, Dynamics and Control*, Springer, pp.55-72.
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e. Others (Patents)	路面状況認識装置、そのプログラム、及び移動体システム, 特願 2015-169850, August, 2015.
(Awards)	Finalist, Young Investigator Fund Best Paper Award，日本 IFToMM 会議，Jun 2017. Best Award, ESJ64 English Presentation Award，日本生態学会，March 2017. 他 3 件