Graduate School of Advanced Science and Engineering
Waseda University

博　士　論　文　概　要
Doctoral Thesis Synopsis

論　文　題　目
Thesis Theme

The Motion Generation of Stable Vertical Ladder Climbing Capable of Recognizing Rungs for a Four-limbed Robot

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Having been a big threat to human since their appearance on the earth, natural disasters have occurred all over the world, very difficult to predict and avoid in advance. Benefited from rapid evolution of robot technology, disaster response robots emerge into our view as a solution instead of human to perform rescue tasks at disaster sites, such as inspection, locomotion, manipulation, cleaning and so on. For some situations frequently seen in the disaster sites, such as uneven roads caused by collapsed buildings, narrow places (space under pipes, between the walls, etc.) and so on, disaster response robots that have been engaged in the disaster sites are capable of dealing with them and finishing tasks after getting over these situations. It is not the case, however, for some environment in disaster sites like vertical ladders with apparent difference in height. Rarely can we see robots with capability of vertical ladder climbing sent to disaster areas, especially for infrastructures where there are ladders instead of elevators to carry human up and down, like nuclear power plants. The requirement of climbing ladders exists not only in disaster sites but also in the maintenance of infrastructures. Representative instances include industrial chimneys and offshore wind turbines with height of more than 100 meters.

Considering the background and present situation of disaster response robots above, a robot with the capability of both ladder climbing and other tasks that existing disaster response robots can perform is highly required. To realize ladder climbing in disaster sites, there are several options of robot platforms available. In this study, human-sized legged robots are chosen instead of other types like snake robots because disaster sites, especially for indoor infrastructures, are designed for human and robots with human size and structure similar to human will be able to adapt environment to the biggest degree. Specifically, the robots used in this study are focused on four-limbed types, which is the same type of human. However, different from human, the four-limbed robots in this study have 4 limbs with the identical design and symmetric layout to guarantee the robustness. With this design, an arbitrary limb can be utilized as both arm and leg without the need of discrimination. In another word, this means that while performing legged locomotion, there is no difference between the top and bottom of the robot and the robot can also perform any legged locomotion (including vertical ladder climbing) with reverse standing, and this design concept is aiming at improving the flexibility of locomotion.

The study of vertical ladder climbing by robots has appeared a few decades. Nevertheless, vertical ladder climbing performed by human-sized robots is relatively later (around 10-20 years) and there are full of unknown areas to be explored. A typical instance is stability for a four-limbed robot on a vertical ladder. Since the contact points that a four-limbed robot or robots with more than 4 limbs can obtain in ladder climbing are more than biped walking, stability analysis of legged robots on a vertical ladder tends to be ignored. However, from previous studies of vertical ladder climbing it is found that ladder climbing in existing research has the limitation of the following: (i) Stable ladder climbing realized by former human-sized robots are mostly in a much slower gait (3-point contact gait), while stable ladder climbing in a faster gait (2-point contact gait) has rarely been realized. (ii) No robot has been succeeded or claimed to succeed in climbing ladder with unknown or irregular specification, which requires capability of recognition of the ladder and corresponding motion planning.

Consequently, from the discussions above, this thesis will mainly focus on the realization of stable vertical ladder climbing with (i) Motion generation system designed for ladder climbing and is compatible with other types of locomotion styles as well; (ii) Sensor feedback systems of ladder climbing motion to guarantee the stability of the robot during ladder climbing, with both force feedback to maintain equilibrium of moment and proximity sensor feedback enabling recognition of ladder rungs and ensures every contact between the robot and ladder is successful. In detail, the aim of this thesis is achieved by:

1) Motion generation system for vertical ladder climbing. Different from other types of locomotion style including multi-legged walking, ladder climbing has its unique features. Based on these features, a generation system for whole-body ladder climbing motion is proposed so that it is “customized” for ladder climbing and compatible with other types of locomotion styles as well. Besides, stability is also considered in whole-body motion generation based on the stability analysis of the robot;
2) Sensor feedback system of ladder climbing motion for stability. A four-limbed robot may fail in keeping ladder climbing for multiple reasons, and this thesis mainly concerns: (i) Maintaining equilibrium of moment for the robot while it is climbing a ladder (especially when there are only 2 contact points); (ii) Guaranteeing successful and appropriate contact between the robot and ladder for each ladder climbing motion. These 2 points are realized by the feedback of force/torque sensors and proximity sensors on the robot.
3) Integration of all systems proposed and developed in this thesis.

This thesis consists of 5 chapters to be presented. They are organized as follows:

- Chapter 1 introduces the background and the social requirement for this research. Brief introduction about previous related studies and comparison between them and this study are shown as well to highlight the novelty and superiority of this study.
- Chapter 2 introduces 2 robots developed by us, “The Prototype” and “WAREC-1” as the hardware platforms of ladder climbing. Their specifications, system configuration and features as well as designs related to ladder climbing are mainly focused, which are also the base of contents for the following chapters.
- Chapter 3 explains the whole-body motion planning and generation system of ladder climbing for four-limbed robots developed by the author. Whole-body motion planning in this thesis consists of the following 3 components: (i) Climbing gaits; (ii) End-effector trajectory planning and (iii) Body trajectory planning. Gaits of ladder climbing motion mainly studied in this thesis and their features are introduced, with corresponding plans of whole-body motion provided. After the climbing gait is determined, end-effector trajectory planning is formulated. In this thesis planning of path and time profile in end-effector trajectory are separated and done independently after the mathematical conversion called “arc-length parameterization” so that spatial and hardware constraints of the robot in ladder climbing can be dealt with individually, making trajectory planning much easier and more flexible. Besides, minimization of path length according to mid-points of the path are proposed as an option in this thesis to shorten the total path that end-effector travels, contributing to the decrease of the total time required in ladder climbing under the same circumstances. Lastly, body trajectory planning is given according to different climbing gaits with consideration of stability. There 3 major parts of (i), (ii) and (iii) form whole-body motion planning in this thesis. Besides, inverse kinematics mainly based on pseudo-inverse of Jacobian is also presented.
- Chapter 4 presents 2 main sensor systems for feedback: (i) Force sensor feedback system with PID reaction force controller manages to reduce the bias of reaction force between hand and foot in 2-point contact

climbing gait, a major cause of failure in ladder climbing. (ii) Proximity sensor feedback system for recognition of ladder rung and error compensation; For (i), the details about the PID controller as well as the calculation of reaction force required for stable 2-point contact ladder climbing are presented. For (ii), details and configuration of proximity sensor system are introduced and algorithm of rung recognition as well as the corresponding motion planning to lead end-effector to the target rung are proposed. Experiments show that proximity sensor feedback system is capable of recognizing a ladder in unknown specifications, such as rung interval and inclination of the rung, with error compensation available. Finally, all contents in Chapter 3 and Chapter 4 are totally integrated and results verify the validity of the integrated systems with discussions.

- Finally, Chapter 5 summarizes the contribution of this thesis in major points. Meanwhile, limits of this thesis and future works based on limits found from the results are given as well.

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)			
1. 論文				
○	Error Compensation System with Proximity Sensors for Vertical Ladder Climbing of the Robot "WAREC-1"	Proceedings of IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids), pp.40-46, 2018	Nov. 2018 (published)	<u>**X. Sun**</u>, S. Hayashi, K. Hashimoto, T. Matsuzawa, Y. Yoshida, N. Sakai, A. Imai, M. Okawara, K. Kumagai, T. Matsubara, K. Yamaguchi and A. Takanishi
	End-effector with a Hook and Two Fingers for the Locomotion and Simple Work of a Four-limbed Robot	Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp.2727-2732, 2018	Oct. 2018 (published)	T. Matsuzawa, A. Imai, K. Hashimoto, T. Teramachi, <u>**X. Sun**</u>, S. Kimura, N. Sakai, Y. Yoshida, K. Kumagai, T. Matsubara, K. Yamaguchi and A. Takanishi
	Crawling and Foot Trajectory Modification Control for Legged Robot on Uneven Terrain	International Journal of Mechatronics and Automation (IJMA)	Aug. 2018 (accepted)	T. Matsuzawa, A. Koizumi, K. Hashimoto, <u>**X. Sun**</u>, S. Hamamoto, T. Teramachi, N. Sakai, S. Kimura and A. Takanishi
	Body Mechanism with Linear Spikes for Slippage Reduction of Four-limbed Robot Crawling on Uneven Terrain	*ROMANSY 22-Robot Design, Dynamics and Control.*, Springer International Publishing, pp.280-287, 2018	Jun. 2018 (published)	T. Matsuzawa, T. Matsubara, K. Hashimoto, T. Teramachi, <u>**X. Sun**</u>, S. Kimura, N. Sakai, Y. Yoshida, A. Imai, K. Kumagai K. Yamaguchi. K. Namura and A. Takanishi
	WAREC-1 - A Four-Limbed Robot Having High Locomotion Ability with Versatility in Locomotion Styles	Proceedings of International Symposium on Safety, Security and Rescue Robotics (SSRR), pp. 172-178, 2017.	Oct. 2017 (published)	K. Hashimoto, S. Kimura, N. Sakai, S. Hamamoto, A. Koizumi, <u>**X. Sun**</u>, T. Matsuzawa, T. Teramachi, Y. Yoshida, A. Imai, K. Kumagai, T. Matsubara, K. Yamaguchi, G. Ma and A. Takanishi

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論文の続き				
	Crawling Gait Generation Method for Four-Limbed Robot Based on Normalized Energy Stability Margin	Proceedings of International Symposium on Safety, Security and Rescue Robotics (SSRR), pp. 223-229, 2017.	Oct. 2017 (published)	T. Matsuzawa, K. Hashimoto, **X. Sun**, T. Teramachi, S. Kimura, N. Sakai, Y. Yoshida, A. Imai, K. Kumagai, T. Matsubara, K. Yamaguchi, W. Tan and A. Takanishi
	A Four-Limbed Disaster-Response Robot Having High Mobility Capabilities in Extreme Environments	Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 5398-5405, 2017.	Sep. 2017 (published)	K. Hashimoto, S. Kimura, N. Sakai, S. Hamamoto, A. Koizumi, **X. Sun**, T. Matsuzawa, T. Teramachi, Y. Yoshida, A. Imai, K. Kumagai, T. Matsubara, K. Yamaguchi,G. Ma and A. Takanishi
○	Planning and Control of Stable Ladder Climbing Motion for the Four-limbed Robot "WAREC-1"	Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 6547-6554, 2017.	Sep. 2017 (published)	**X. Sun**, K. Hashimoto, T. Teramachi, T. Matsuzawa, S. Kimura, N. Sakai, S. Hayashi, Y. Yoshida and A. Takanishi
	Crawling Motion and Foot Trajectory Modification Control for Legged Robot on Rough Terrain	Proceedings of IEEE International Conference on Mechatronics and Automation (ICMA), pp. 1977-1982, 2017.	Aug. 2017 (published)	T. Matsuzawa, A. Koizumi, K. Hashimoto, **X. Sun**, S. Hamamoto, T. Teramachi N. Sakai, S. Kimura and A. Takanishi
○	Trajectory Generation for Ladder Climbing Motion with Separated Path and Time Planning	Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp.5782-5788, 2016.	Oct. 2016 (published)	**X. Sun**, K. Hashimoto, S. Hamamoto, A. Koizumi, T. Matsuzawa, T. Teramachi and A. Takanishi

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論文の続き				
	Crawling Gaits for Four-limbed Robot and Simulation on Uneven Terrain	Proceedings of IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids), pp.1270-1275, 2016.	Nov. 2017 (published)	T. Matsuzawa, A. Koizumi, K. Hashimoto, X. Sun, S. Hamamoto, T. Teramachi, S. Kimura, N. Sakai and A. Takanishi
○	Path-Time Independent Trajectory Planning of Ladder Climbing with Shortest Path Length for a Four-limbed Robot	Proceedings of 6th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp.188-194, 2016.	Aug. 2016 (published)	X. Sun, K. Hashimoto, A. Koizumi, S. Hamamoto, T. Matsuzawa, T. Teramachi and A. Takanishi
	End-Effector for Disaster Response Robot with Commonly Structured Limbs and Experiment in Climbing Vertical Ladder	*ROMANSY 21-Robot Design, Dynamics and Control.*, Springer International Publishing, pp.311-319, 2016.	Jan. 2016 (published)	T. Matsuzawa, K. Hashimoto, T. Teramachi, K. Uryu, X. Sun, S. Hamamoto, A. Koizumi and A. Takanishi
	その他 2 件			
2. 講演				
	極限環境下で作業可能な災害対応ロボットに関する研究（第２４報：胴体接地を活用した段差踏破が可能な４肢ロボットの開発）	第 36 回日本ロボット学会学術講演会, 1D3-07	2018 年 9 月	名村圭祐，松澤貴司，橋本健二，孫瀟，酒井伸明，林翔太，吉田雄貴，今井朝輝，大河原正篤，熊谷健吾，松原孝将，山口航希，内藤博，高木一輝，高西淳夫
	その他 20 件			