Development and Control Method of Six-Wheel Robot with Rocker Structure

Keiji NAGATANI, Ayato YAMASAKI, Kazuya YOSHIDA
Tohoku University
6-6-01, Aramaki-Aoba
Aoba-ku, Sendai, Miyagi 980-8579, Japan
keiji@ieee.org

Tadashi ADACHI
IHI Aerospace
900 Fujiki, Tomioka-city,
Gunma 370-2398, Japan
a-tadashi@iac.ihi.co.jp

Abstract — In our research group, the project, named "networked robotic system for disaster mitigation", has been carried out to perform robotic victim-search in disaster environment. In this project, we have developed a mobile robots' system which consists of small mobile robots (to search victims in collapsed buildings) and a large-mobile-robot (to convey small robots into it). In order to approach to the target buildings, the large robot is required to surmount some debris and bumpy terrain. For this purpose, the robot has six wheels, and two pairs of wheels in front are formed as actuated rocker structures. This wheel configuration can achieve "active load-equalizer" or other control methods by using load cell data. In this paper, the system description and control methods of the large robot are introduced. We also report a performance of the control methods using a "robot dynamics simulator" developed in our group and preliminary experiments using real robot to evaluate the feasibility of our approach.

Keywords: *Rocker Structure, Rough terrain*

I. Introduction

In the field of earthquake disaster, prompt rescue works are strongly required. However, rescue crews are exposed in danger in such environments because of secondary disaster caused by aftershocks. In these circumstances, a demand of rescue robots has been increased recently. Particularly, the development of remotely operated robots for immediate surveillance is strongly expected from the robotics community[1].

Since 2003, our research group have been working on a novel project based on a networked robotic system to mitigate disasters in an urban earthquake-stricken areas [2][3], under the support of the Japanese Ministry of Internal Affairs and Communications (MIC). The project aims at developing a teleoperated robotic system for surveillance. To be able to tackle surveillance tasks with a robotic technology in an urban disaster environment, we have developed a multi-robots system. It consists of (1) a large-scale outdoor robot (to survey outside and to deploy small-robots in damaged buildings) and (2) small-scale indoor robots (to survey inside the buildings).

The large robot which we have been developing (Fig.1) has six wheels with rocker structures. Basically, the large robot is tele-operated manually. However, for easy operation, surmounting small debris or adaptation of rough terrain should be performed automatically. To realize such functions, conventional six wheels' robots (such as Mars rover [4] or Shrimp [5]) has passive rocker structures. Instead of passive mechanism, we chose active mechanism. It requires two more additional powerful motors (and load-cells) to perform "active load-equalizer" which enables a similar function as standard passive rocker-links. However, it has an additional advantage, "high ability of surmounting" by using the actuated rocker structure as a kind of "leg-wheeled robots". In this case, the robot is operated by full-manual control or model-based control.

Fig. 1. Our developing six-wheels large robot

In this research, we aim at evaluating some control methods for the large robot's locomotion with autonomous or manual terrain (or bumpy surface) adaptation, specifically for the rocker joints' actuation. The "Robot dynamics simulator", which we developed, is one good tool for formulating and evaluating different control methods. In this paper, we present (1) the target system of the large robot, (2) some control methods of its locomotion, and finally (3) evaluation and comparison of them based on the simulation and real robot.

II. System requirement and system description

In the scenario of this research project, the large robot should have a capability to check on the damage of disaster area, to surmount steps and debris with mounting several small robots, and to deploy the small robots into an upper floor.

Fig. 2. A large robot with extendable ramp

On the other hand, its total weight must not exceed a weight limit of large-size-helicopter to carry them. With consideration above, we determined a requirement of large robot as follows.

1) Total weight: less than 500[kg]
2) Maximum speed: more than [4km/h]
3) Six independently driven wheels and steering
4) Actuated rocker mechanism (for front two pairs of wheels)
5) Embedded load cell for each wheel's support strut
6) Extendable ramp to deploy small robots
7) Three-dimensional range sensor and omni-vision sensor (see [3], not discussed in this paper)

Based on the above requirement, IHI corporation have been developing a prototype of large robot which mounts an extendable ramp for our research project. An overview of deployment of small robots using its extendable ramp are shown in Fig.2.

A. Mechanism of locomotion of large robot

Generally, it is said that maximum step-height which a wheel can surmount is less than the radius of the wheel. Therefore, larger wheels have an advantage of negotiating bumpy areas. However, in our research project, there is a trade off between wheels' diameter and a limitation of size (or weight) in robot's carrier.

To provide a capability of surmounting step for the robot as much as possible, we adopt the rocker mechanism for locomotion of the robot. An schematic of its structure is shown in Fig.3. The front wheel and the middle wheel are connected by a rocker-link each other, and two pairs of them are located at the front of the robot. The rocker joints are actuated independently to surmount large steps and to adjust the height differences caused by an uneven ground.

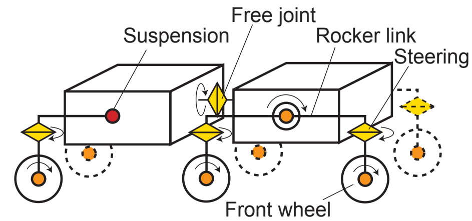

Fig. 3. Structure of large robot for rough terrain

Basically, maxon motors (24V, 250W) are used for wheels and rocker joints. the Gear ratio of locomotion motors is 213:1, and the gear ratio of the rocker joints is 2799.65:1.

B. Basic locomotion maneuvers

The locomotion mechanism shown in the above has redundancy: six independently driven wheels and steering. (Totally, it has 12 motors except rocker mechanism.) Therefore, the locomotion system requires constraints even if it just enables basic locomotion maneuvers. Motion modes which enables basic motion on a planar environment are shown as follows.

1) Translational motion: To realize a translational motion of the robot, all steering motors should be aligned in the same orientation, and the locomotion motors should be controlled in the same angular speed. In this mode, according to the steering angle value, the robot moves in omni-direction (translational motion of longitudinal direction, lateral direction and oblique direction with keeping robot's orientation).

2) Cornering motion: In assumption of following a given curve in Fig.4, steering angles of the front wheel and the rear wheel are kinematically constrained kinematically in the following equations,

$$\alpha_{Fl} = \tan^{-1}\left(\frac{2L\tan\alpha}{2L - T\tan\alpha}\right) \quad (1)$$

$$\alpha_{Fr} = \tan^{-1}\left(\frac{2L\tan\alpha}{2L + T\tan\alpha}\right) \quad (2)$$

$$\alpha_{Rl} = -\alpha_{Fl} \quad (3)$$

$$\alpha_{Rr} = -\alpha_{Fr} \quad (4)$$

where α is the steering angle of hypothetical wheel (which is located between left wheel and right wheel virtually), R is the rotational radius, T is the half length of tread, L is the half length of wheel base, subscripts of Fl, Fr, Rl, Rr mean front left, front right, rear left rear right wheel respectively.

To adjust rotational speed, the rotational speed of each wheel is controlled by using the rotational speed of virtual wheel in the following equations,

$$\omega_{Fl} = \omega_{Rl} = \frac{\sin\alpha}{\sin\alpha_{Fl}}\omega \quad (5)$$

$$\omega_{Fr} = \omega_{Rr} = \frac{\sin\alpha}{\sin\alpha_{Fr}}\omega \quad (6)$$

$$\omega_{Ml} = \frac{\sin\alpha}{\tan\alpha_{Fl}}\omega \quad (7)$$

$$\omega_{Mr} = \frac{\sin\alpha}{\tan\alpha_{Fr}}\omega. \quad (8)$$

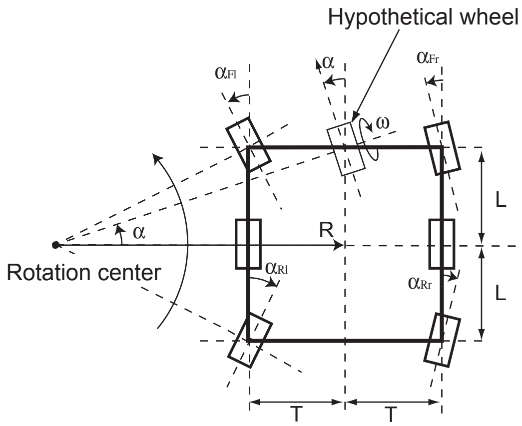

Fig. 4. Kinematic constraint of curving motion

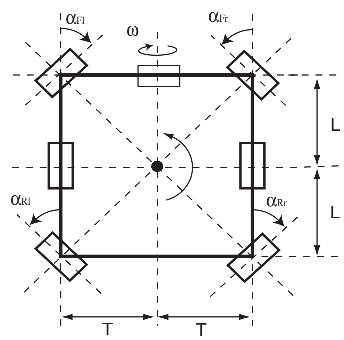

Fig. 5. Kinematic constraint of turning motion

3) Turning motion: For turning motion shown in Fig.5, steering angles of each wheel is kinematically constrained in the following equations,

$$\alpha_{Fl} = \alpha_{Rr=} - Tan^{-1}\left(\frac{L}{T}\right) \quad (9)$$

$$\alpha_{Fr} = \alpha_{Rl} = -\alpha_{Fl}. \quad (10)$$

In this case, each wheel speed is expressed as,

$$\omega_{Fl} = \omega_{Rl} = -\frac{\omega}{\sin\alpha_{Fl}} \quad (11)$$

$$\omega_{Fr} = \omega_{Rr} = -\omega_{Fl} \quad (12)$$

$$\omega_{Ml} = -\omega_{Mr} = -\frac{T\omega}{L}. \quad (13)$$

C. Performance test

In March 10th, 2006, our research project conducted a demonstration of the robot motion to release our research to the media[6]. In the demonstration, the large robot is navigated remotely on planar field by joystick, and surmounted small steps without controlling actuators of rocker joint (see Fig.6). Then it deployed two small robots to 2nd floor of the building using extendable ramp. According to the demonstration, we confirmed a basic function of locomotion and deployment function for small robots. However, the robot did not perform its potential ability yet, particularly actuators of rocker joint were never used to surmount obstacles.

Fig. 6. A performance test of surmounting steps for large robot

III. Robot dynamics simulator

To understand a behavior of robots, experiments using actual robots in many fields are very important. However, particularly heavy robots such as our large robot, it is not an effective approach to use actual robots blindly from the point of view of the number of trials and safety of the robot. Instead, we developed robot simulator of the large robot to understand its behavior. ODE (Open Dynamics Engine) is used for the core of the simulator. In this section, the simulator and some performance tests using the simulator is introduced.

A. Modelling of large robot

Fig.7 shows a model of the large robot which is used in our simulator. Its size and its degrees of freedom of the simulated robot are the same as actual large robot, and we set the total weight as 420[kg], front (and rear) weight of the body as 80[kg] and each wheel as 37[kg]. A load cell is embedded in each wheel's support strut, just the same as the real robot. An objective of the simulator is to understand the robot's basic performance, so the extendable ramp is not mounted on the virtual robot to simplify the robot. Other conditions in the simulator are as follows:

1) The coefficient of friction is set as 0.5, and the coefficient of rebound is set as 0.1 respectively.
2) Default speed of the robot is set as 0.3 [m/s].
3) Rotational speed of each wheel is controlled by PI-control.
4) Steering angle of each wheel is controlled by PID-control.
5) The virtual robot has two modes. One is "Manual mode"to be controlled by joystick (just the same as the actual robot). The other is "Auto mode" to be controlled by program.

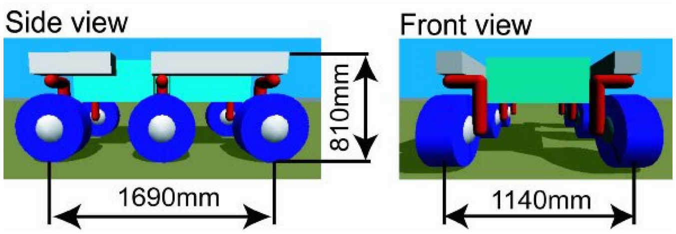

Fig. 7. Model of virtual robot

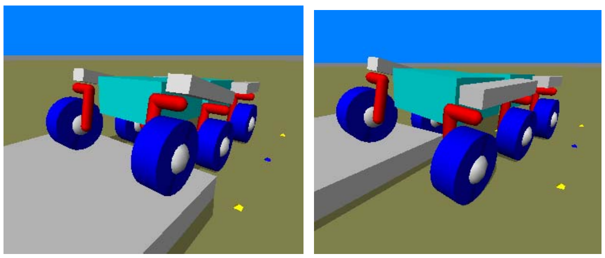

Fig. 8. Surmounting a step with passive rocker joint

B. Surmounting ability with passive rocker joints

Our first simulation is to perform surmounting motion without controlling actuators of rocker joints. Fig.8 show scenes of both complete surmounting (left) and one-side surmounting (right). In both case, the virtual robot moves forward toward the step according to the joystick input. However rocker joints are not controlled, instead it changes the angle passively according to the balance of dynamics between wheels and the ground.

By repetition of simulations with various heights of the step (in 1[cm] resolution), we found that the maximum height of step to surmount in complete manner (all wheels are on the step) was 21[cm]. On the other hand, the maximum height of step to surmount in one-side (half wheels are on the step) was 13[cm]. The reason of the height difference is as follows. In the former case, the two front wheels touch to the step simultaneously, and the transition of the robot's body stops for a moment. However, in the latter case, one side of wheels move normally with nonstop, but the front wheel in the other side is caught by the step. Then it causes bouncing up of the middle wheels.

C. Surmounting ability with manual control of rocker joints

Next simulation is to perform surmounting motion with manual control of rocker joints. In this case, the virtual robot moves forward toward the step according to the joystick input, and the two rocker joints are controlled manually.

Fig.9 shows a sequence photographs of surmounting motion in manual control of rocker joints. By repetition of simulations with various heights of the step (in 1[cm] resolution), we found that the maximum height to surmount in complete manner was 85[cm]. On the other hand, the maximum height of step to surmount in one-side was 60[cm]. The reason of the height difference was that the rear body is got stuck with the step because the joint between the front body and the rear body was twisted, in the latter case.

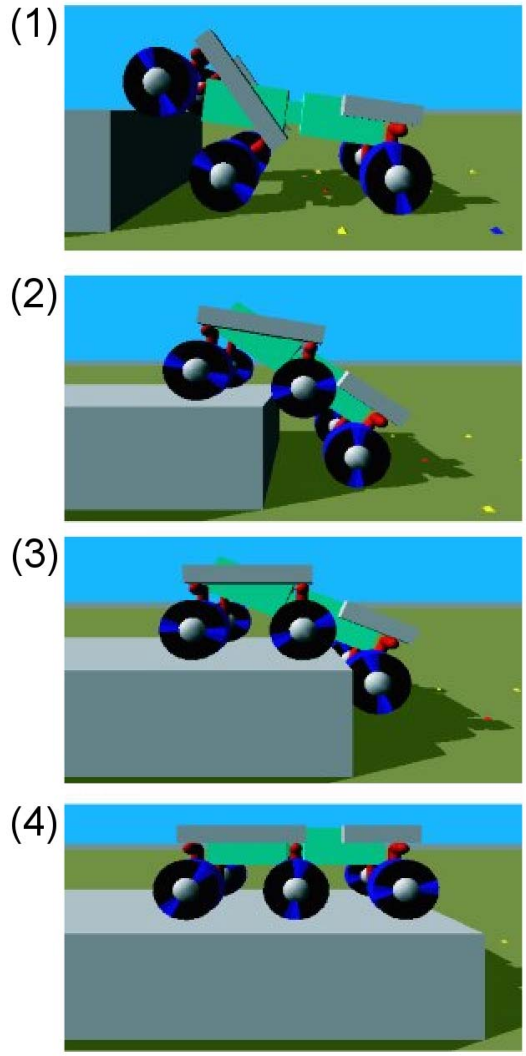

Fig. 9. Surmounting scequence with manual control of rocker joints

In intuition, the surmounting ability seems to depend much on a skill of operator. However, in this evaluation, the operator is well trained (he is also the developer of the simulator) and the result seems to to be the theoretical one mostly.

D. Evaluation of active load-equalizer of rocker joints

In case that the operator (or the robot itself) knows a step height to surmount, the manual control shown the above method is enough. However, in practical case, environmental information acquired by sensors is not sufficient for operation. Furthermore, there exists a time-delay of the wireless network.

Therefore, an autonomous control for rocker joints is one key issue for tele-operation of our robot. “active load-equalizer” of rocker joints is the first coming idea for stable navigation of the robot on bumpy surface. Fig.10 expresses one good example of necessity of such a control. The figure shows transition graphs of values of load cell data (which are

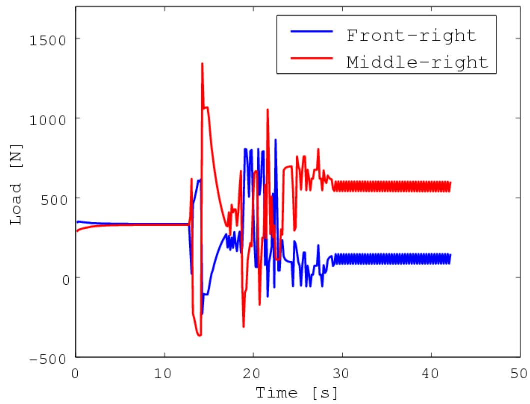

Fig. 10. Reactive forces in case of passive rocker joints

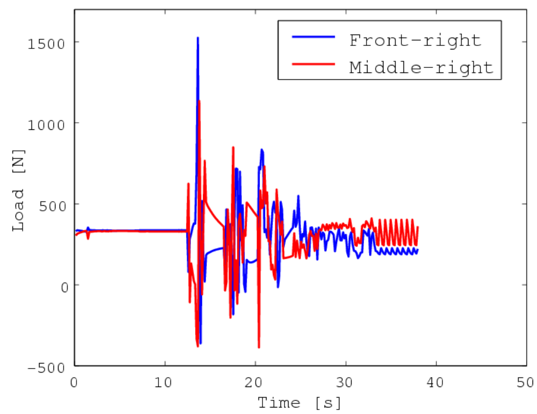

Fig. 11. Reactive forces in case of active load-equalizer

embedded in the strut of the front and the middle wheels) when the virtual robot surmounts a step in complete manner in the simulator. It is obvious that the final values of the load cells are not equivalent, and it may generate an insufficient traction force because of unbalance of load distribution.

Using the values of the load cell data, active load-equalizer can be realized by local feedback loop. It is based on the position control of the rocker joint angles to keep the front and the middle load cell data equivalently. Fig.11 shows transitions of load cell data when the active load-equalizer is working in the simulator. It is seen that the values are converged into almost the same value finally, and it is expected a sufficient traction force.

However, from the point of view of surmounting ability, maximum step height is only 20 [cm], which is 1[cm] lower than the maximum height in the case of passive rocker joints.

E. Evaluation of load-distribution control of rocker joints

According to the previous subsection, active load-equalizer is good for maintaining traction force, but not good for surmounting a step. To improve an ability of surmounting step of the robot using autonomous feedback control, we implemented load-distribution control in the virtual robot.

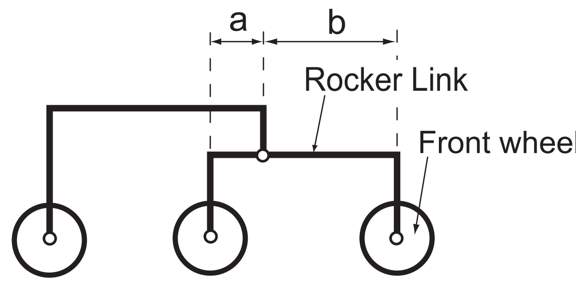

Fig. 12. Position of rocker joint

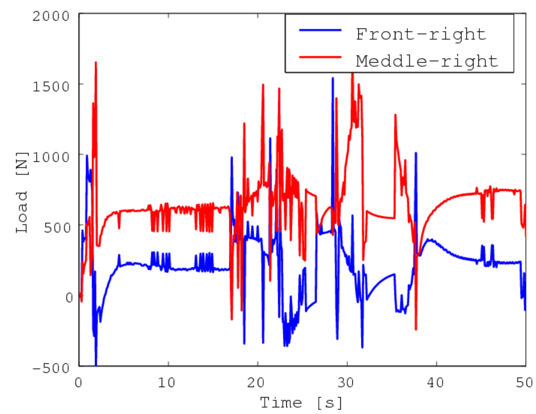

Fig. 13. Reactive force under distributing load control

Basically, the joint of the rocker link is located at the median of the bar. If the joint location is moved to backward as shown in Fig, it is easier for the wheel to bounce up when the front wheel touches to a step.

Basically, the joint of the rocker link is located at the median of the bar. If the joint location is moved to backword as shown in Fig.12, it is easier for the wheel to be bounced up when the front wheel touches to a step. Of course, it is difficult to change the mechanism of actual length of the rocker link bar, so we implemented a controller to keep a fixed ratio of load-distributions which are detected by load cells.

A simulation result of the control of "keeping a fixed ratio of load-distribution" is shown in Fig.13. In the simulation result, the ratio $(a : b)$ is set as $1 : 3$, and the virtual robot succeeded in surmounting 23 [cm] step height. The height is 3 [cm] higher than the maximum surmounting height in case of active load-equalizer. If the parameter b in the ratio is larger than 3, the front wheel is easier to bounce up. However, in this case, it was happened that the middle wheel did not surmount the step, instead it rotated around the joint axis. Therefore, we set the ratio as $1 : 3$ by empirical approach.

Using the above method, the ability of surmounting step is improved. However, it reduces the performance of traction force caused by un-balanced distribution of load. Therefore, we understand that we should consider a trade-off between uniform distribution of the load to maintain good traction force and un-balanced distribution of the load to surmount steps.

Fig. 14. Experiment scene

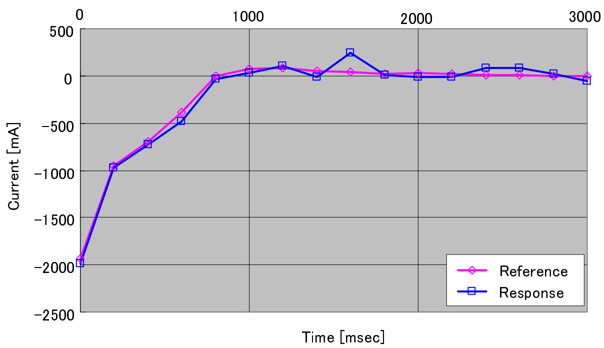

Fig. 15. Experimental result of active load-equalizer using the actual robot

IV. Preliminary experiments using real robot

We have implemented "active load-equalizer" of rocker joints on the real robot, and conducted preliminary experiments. In this experiment, we set an initial configuration of the robot as shown in the Fig.14, and there existed a load values' difference between the front and the middle wheels. Then the active load-equalizer was started at 0 [msec]. Fig.15 shows the result of the reference current transition (colored by magenta) and the actual current transition (colored by blue). In this experimental setup, the reference current to actuate one rocker joint was calculated by the difference between two load cells' data (located at the front wheel and the middle wheel). Then the actual current was performed to follow the reference value. After 1000 [msec], the reference converged into "0", and the load-equalizer was worked properly.

V. Conclusion

In this paper, an overview of the large six-wheel mobile robot constructed in our research project was introduced. To improve its locomotion performance, several control methods for the robot were performed by the "Robot Dynamics Simulator". Finally, one control method, "active load-equalizer", was implemented on the real robot in preliminary experiments. The large robot is now in tuning phase, and it was impossible to perform field tests by it. In near future works, we perform some field tests and compare it with simulation results which we obtained as shown in this paper.

In the next steps, we have two possible approaches to improve its locomotion ability. One is model-based-approach, and the other is sensor-based-approach. In the former approach, the robot acquires the environment model using three dimensional range sensor, and plans its motion based on the model. In the latter approach, the robot detects the force from load cells, and moves rocker joints reactively. We are planning to clear advantages and dis-advantages in various environmental situations.

Acknowledgment

This project is supported by SCOPE-R in the Japanese Ministry of Internal Affairs and Communications since 2003.

References

[1] Special issue of advanced robotics: Advanced research and development of robotics for search and rescue. *Journal of Advanced Robotics*, 19(3):219–347, 2005.

[2] K. Yoshida, K. Nagatani, K. Kiyokawa, Y. Yagi, T. Adachi, H. Saitoh, H. Tanaka, and H. Ohno. Development of a networked robotic system for disaster mitigation, test bed experiments for remote operation over rough terrain and high resolution 3d geometry acquisition. In *Proceedings of of the 5th International Conference on Field and Service Robotics*, pages 333–343, 2005.

[3] Andres E. Mora Vargas, Kenzuke Mizuuchi, Daisuke Endo, Eric Rohmer, Keiji Nagatani, and Kazuya Yoshida. Development of a networked robotic system for disaster mitigation –navigation system based on 3d geometry acquisition–. In *Proceedings of the 2006 IEEE International Conference on Intelligent Robots and Systems (IROS '06)*, pages 4821–4826, Beijing, China, 2006.

[4] Brian D. Harrington and Chris Voorhees. The challenges of designing the rocker-bogie suspension for the mars exploration rover. In *37th Aerospace Mechanisms Symposium*, 2004.

[5] T.Estier, Y.Crausaz, B.Merminod, M.Lauria, R.Piguet, and R.Siegwart. An innovative space rover with extended climbing alilities. In *Proceedings of Space and Robotics 2000*, 2000.

[6] Keiji Nagatani, Kazuya Yoshida, Kiyoshi Kiyokawa, Yasushi Yagi, Tadashi Adachi, Hiroaki Saitoh, Toshiya Suzuki, and Osamu Takizawa. Development of a networked robotic system for disaster mitigation -system description of multi-robot system and report of performance tests-. In *Proceedings of the 6th International Conference on Field and Service Robotics*, page to be appeared, 2007.