Semi-autonomous Traversal on Uneven Terrain for a Tracked Vehicle using Autonomous Control of Active Flippers

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***Abstract*— Active flippers for tracked vehicles are very useful to improve traversability on uneven terrain. However it is widely known that control of flippers also increases the work-load for operators, particularly where the vehicle and the operator are far apart. To reduce the work-load, we aim to realize a sensor-based autonomous controller of flippers to enable a "semi-autonomous operation" of tracked vehicles. The "semi-autonomous operation" means that the only requirement for an operator is to indicate the robot's direction. In this way, the robot is navigated autonomously through its sensors and actuators to surmount or avoid obstacles. In this research, two laser range sensors are used for terrain sensing, and gyro sensors are used for the measurement of the robot's attitude. Based on such sensor system, we propose a strategy of simple sensor-based motion of active flippers for tracked vehicles to enable a semi-autonomous operation. In this paper, we introduce a strategy of motion of active flippers, and the stability analysis of tracked vehicles with active flippers. Finally, we report several experimental results to verify the validity of our approach.**

I. INTRODUCTION

In urban earthquake disasters, it is a very dangerous task for the rescue crew to search for victims under circumstances of aftershocks. Therefore, remote controlled mobile robots can be great help for searching inside of collapsed buildings instead of the rescue crew.

With such social demands as a background, activities of research and development of rescue robots are increasing all over the world. Our group has also been performing research on remote control of rescue robot and mapping of wide areas. In this research, tracked vehicles with active flippers have been used for experiments to go up/down stairs and to traverse uneven terrains. Through such experiments, we understood that such flippers drastically improve the traversability on uneven terrains. Fig. 1 shows one example which flippers work effectively on an uneven terrain. However, it also increases the work-load for operators controlling the robots, particularly where the vehicle and the operator are far apart. To reduce the work-load, we considered the design of a sensor-based autonomous controller of flippers to enable "semi-autonomous operation" of tracked vehicles. The purpose of this research is to implement such strategy and to confirm its validity using an actual robot in a simulated disaster environment.

One of features of this research is the use of laser range sensors for terrain sensing. The tracked vehicle has two small laser range sensors whose scan planes are set in parallel to the workspaces of the active flippers and perpendicular to the ground. Gyro sensors also measure the roll and pitch angles of the robot. These sensors enable a real-time sensor-based motion of the flippers to traverse uneven terrains. In this research, we also consider the risk of the robots tipping-over. In this research, we apply the "Static stability criterion" to the stability analysis of our tracked vehicle. Based on the above, the robot generates sensor-based motion of active flippers to realize stable traversability on uneven terrain with consideration of safety.

Fig. 1. Tracked vehicle with active flippers traversing on random step field

In this paper, we introduce a traversing strategy and a stability analysis of uneven terrain for a tracked vehicle which has active flippers. We also reports several experiments using an actual tracked vehicle in a simulated disaster environment to confirm the validity of our method.

II. RELATED WORKS

There is a number of researchers that have created different mechanisms, methods, ways to traverse uneven terrains using mobile robots (particularly wheeled mobile robots). Tani's group [1] and Hasegawa's group [2] developed wheeled mobile robots with active suspensions. Recently, Hirose's group developed a leg-wheel hybrid robot [3]. A common background of the above activities is the control of the wheels' position actively to adapt to uneven terrain.

In the field of tracked vehicles, it is known that active flippers improve the traversability on uneven terrains. Packbot produced by iRobot proved an effectiveness of such mech-

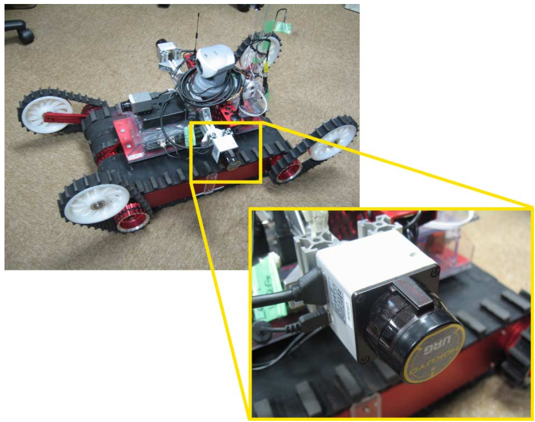

Fig. 2. Our tracked vehicle with laser range sensors

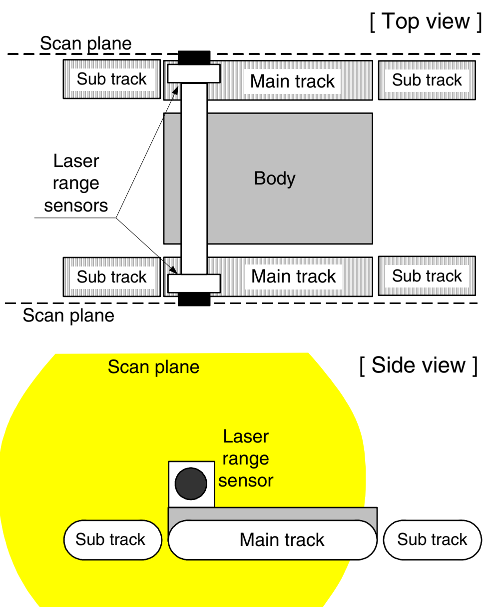

Fig. 3. Installation position of laser range sensors

anism. Recently, many tracked vehicles which participate in Robocup Rescue League [4] have such active flippers. However, it requires highly skilled operators, particularly in remote operation scenarios. To reduce such operator's work-load, there are some reports on which active flippers are controlled automatically to traverse uneven terrains. The most applicable sensor-based method seems to be Tadokoro's approach [5] which uses contact sensing information between flippers and the ground. However, it is also reported that the method is difficult to apply to a large gap without additional sensors. A feature of our approach is to use laser range sensors to detect terrain information and to control flippers with simple rules.

III. AUTONOMOUS TRAVERSING STRATEGY ON UNEVEN TERRAIN

In this research, we use sensor-based motion of active flippers for tracked vehicles to traverse on uneven terrains.

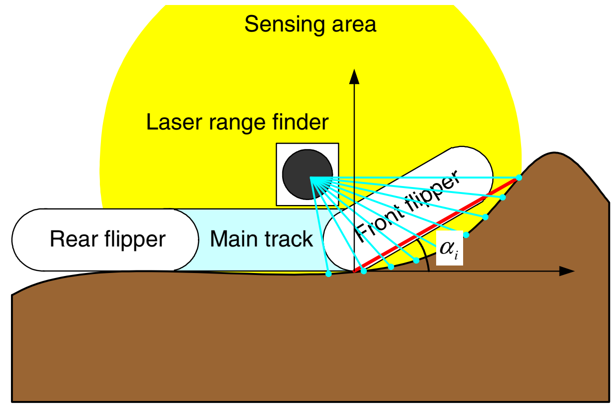

Fig. 4. Strategy of autonomous control of flippers based on range data acquired by laser range sensors

To enable such motion, we use two laser range sensors and gyro sensors (to measure roll angle and pitch angle of the body). Using these sensors, our strategy is shown as follows.

A. Experimental robot

The experimental robot "KENAF" has been developed in our joint research project. Fig.2 shows an overview of the target robot and the positioning of the laser range sensors. The robot's weight is about 20 kilograms, and it has a width of 450 millimeters, a length of 580 millimeters, and a height of 300 millimeters. This robot has four active flippers (each has a length of 280 millimeters) actuated independently to adapt to uneven terrains. The bottom surface of the vehicle is covered with two main tracks which are designed to avoid stranding on obstacles. Standard KENAF has three cameras for remote operation: pan-tilt camera, front camera and bird's-eye camera.

In our tracked vehicle, two laser range sensors (URG-X04) are mounted on both sides of the robot, which are shown in Fig. 2. To detect the surface information of the terrain which flippers contact, each scan plane is parallel to the workspaces of the active flippers and perpendicular to the ground, as shown in the Fig.3. In addition, three gyro sensors are embedded inside its body to measure its attitude (angles of roll, pitch, and yaw). In this research, two gyro sensors are used to measure roll angle and pitch angle.

B. Flipper angles to adapt to uneven terrains

To determine a suitable flipper angle to adapt to uneven terrains, the robot uses range data obtained by laser range sensors.

The robot continuously receives a number of measured points around a contact domain of each flipper. Then, the candidate of each flipper angle α_i is simply determined by contacting the flipper with one measured point which maximizes α_i. Fig.4 shows how the candidate angle α_i is obtained.

Subsequently, the reference angle of the right front flipper based on range data, ϕ_{fr}, is determined by the following

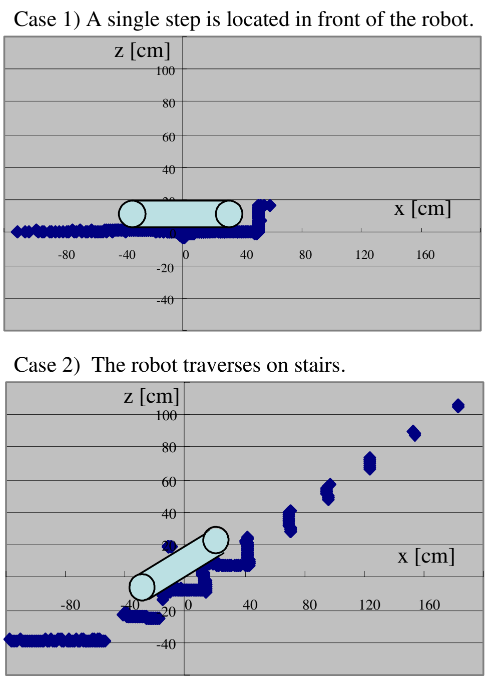

Fig. 5. Sensed set of data obtained by a laser range sensor (To recognize a scale of its sensing domain, the robot's body shape without flippers is drawn at the center.)

equation:

$$\phi_{fr} = \begin{cases} \alpha_i & (\alpha_i \leq \theta_{max}) \\ \theta_{max} & (\alpha_i > \theta_{max}), \end{cases} \tag{1}$$

where θ_{max} is the upper limit of the rotation of the flippers. In this research, we set θ_{max} as 45 degrees. The limit effects to push the ground by flippers when the tracked vehicle climbs over large obstacles.

The other three reference flipper angles $\phi_{fl}, \phi_{rr}, \phi_{rl}$ are also obtained in the same procedure as above.

Fig.5 shows examples of an actual sensed set of data which was obtained by a laser range sensor. In the upper figure, the robot was located in front of a single step on flat ground. In the lower figure, the robot was located on stairs.

C. Control of flipper angles to keep robot's stability

While both sides of the tracked vehicle climbs over a single step, the pitch angle of the body is increased, until the center of gravity of the vehicle gets over the step edge. In such case, a skilled operator usually controls the rear flippers to push the ground. As a result, the pitch angle is suppressed and this operation reduces the landing impact of the body when the center of gravity of the body gets over the step edge. Thus, in order to control the rear flippers is very important to consider the pitch angle of the body.

On the other hand, while one side of the tracked vehicle climbs over a single step, the roll angle of the body is generated. In such case, skilled operators usually controls the left or right flippers to push the ground. As a result, the roll angle is suppressed avoiding to tip-over in the roll direction. Therefore, to control the left or the right flippers, it is very important to consider the roll angle of the body.

The above phenomena occurred simultaneously in many occasions. To be able to autonomously stabilize the roll angle and pitch angle of the body, we set two upper limits θ_{rmax} for roll angle and θ_{pmax} for pitch angle. Based on these limits, the adjustment roll angle ψ_{roll} and the adjustment pitch angle of the body ψ_{pitch} are calculated as follows:

$$\psi_{roll} = \begin{cases} \theta_r - \theta_{rmax} & (\theta_r > \theta_{rmax}) \\ 0 & (|\theta_r| \leq \theta_{rmax}) \\ \theta_r + \theta_{rmax} & (\theta_r < -\theta_{rmax}) \end{cases} \tag{2}$$

$$\psi_{pitch} = \begin{cases} \theta_p - \theta_{pmax} & (\theta_p > \theta_{pmax}) \\ 0 & (|\theta_p| \leq \theta_{pmax}) \\ \theta_p + \theta_{pmax} & (\theta_p < -\theta_{pmax}). \end{cases} \tag{3}$$

The above equations mean that the robot does not control roll and pitch angles when these angles are kept in small.

D. Determination of the flipper angle

The flipper angles are controlled with reference to the angles, $\theta_{fr}, \theta_{fl}, \theta_{rr}, \theta_{rl}$, determined by the scan data from the laser range sensors. Furthermore, to keep the stability of the robot's attitude, the reference angles are adjusted to be $\psi_{roll} = 0$ and $\psi_{pitch} = 0$. In our current implementation, a "bang-bang control" is used to determine the amounts of adjustment. Each flipper reference angle is updated every 100 milliseconds based on the above procedure, which is independent from the control of the forward/backward rotation of the main tracks.

IV. STABILITY ANALYSIS

In this research, we apply the "Static stability criterion" (proposed by Tsukakoshi and Hirose [6]) to our stability analysis of tracked vehicles. The criterion was originally invented for legged locomotion robots. In this criterion, the stability margin S_{NE} is defined as:

$$S_{NE} = h_{max} - h_0, \tag{4}$$

where h_0 represents a height of center of gravity of the body, and h_{max} represents the maximum height of center of gravity of the body while the robot is assumed to tipping over. Therefore, the bigger the value of the S_{NE} is, the more stable the robot is. Note that practical stability analysis for our target robot is very complicate because each flipper can be controlled independently. To simplify the problem, in the following analysis, we assume a symmetric flippers motion of the target robot.

Firstly, we consider the pitch angle direction. In the case of our tracked vehicle, there are two scenarios in which the pitch angle of the body should be determined kinematically. One is the main tracks contact to the ground shown in the upside of Fig.6, and the other is that the rear flippers contact to the ground shown in the downside of Fig.6.

The variables to determine a height of the center of gravity of the body are: (1) the rear flipper angle $\theta_{rr,rl}$, and (2) the pitch angle of the body θ_{pitch}. Using the two variables, a

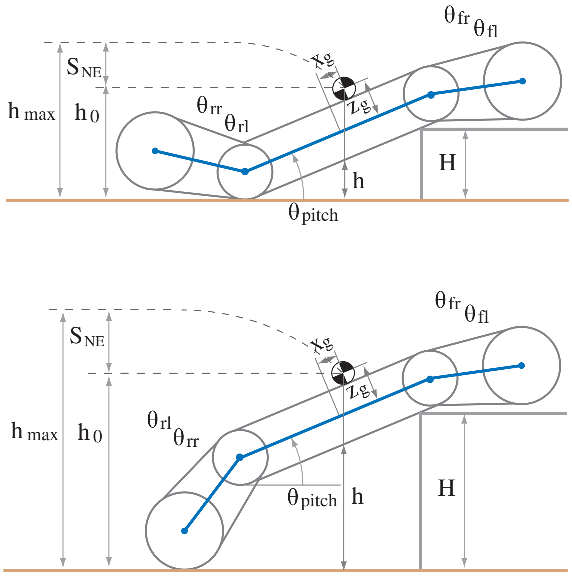

Fig. 6. Pitch angle configuration of our tracked vehicle

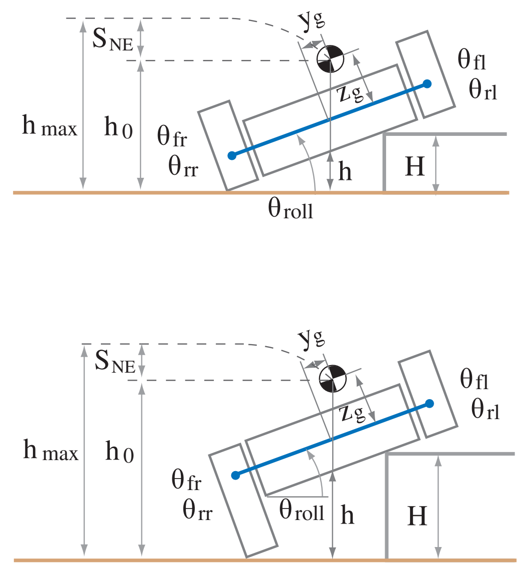

Fig. 8. Roll angle configuration of tracked vehicle

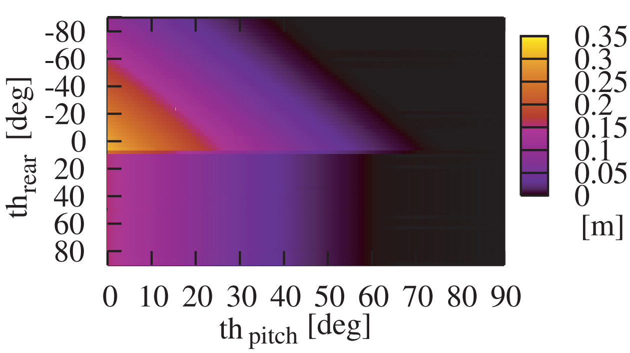

Fig. 7. Distribution of S_{NE} of our tracked vehicle in the pitch angle

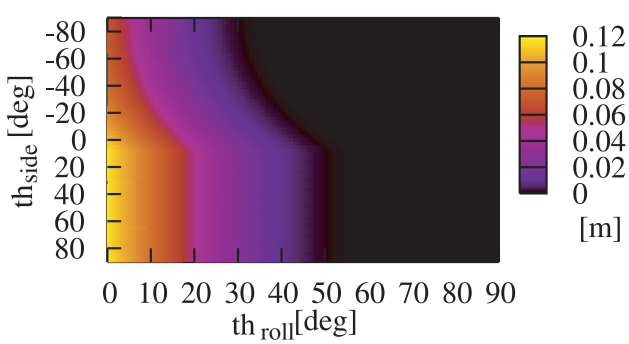

Fig. 9. Distribution of S_{NE} of our tracked vehicle in the roll angle

distribution of S_{NE} is displayed in three-dimension, shown in Fig. 7. In this graph, it is observed that there is a discontinuous plane of stability margin S_{NE}. The reason is that there are two situations shown in Fig. 6, and a fulcrum position to tip over changes from the rear of the main tracks to the rear of flippers.

The application of the S_{NE} graph for stability on the pitch direction is explained as follows. When we assume a stability margin as the 30 percent of S_{NE} in case that the robot stays at horizontal plane, the margin of S_{NE} is 0.15 meters in the pitch direction. Therefore, we can define a stable area in the graph shown in Fig. 7, to be $S_{NE} > 0.15$ meters. If the condition of the robot locates out of this area, it should stop moving motion and abort its task to avoid tipped over.

Secondly, we consider the roll angle direction. In this research, we assume that both left-front and left-rear flippers' angles generate a symmetrical motion to simplify the problem. This case also has two scenarios where is necessary to determine kinematically the the roll angle of the body. One is that main tracks contact the ground shown in the upside of Fig.8, and the other is that the left or right flippers contact to the ground shown in the downside of Fig.8.

The variables to determine the height of center of gravity of the body are: (1) roll angle of the body and (2) one of the left or right flipper angles (because of the flippers' symmetry). Using the two variables, a distribution of S_{NE} is displayed in three-dimension, shown in Fig. 9. In this graph, it is observed that there is a discontinuous plane of stability margin S_{NE} too. The reason is that there are two situations shown in Fig. 8, and a fulcrum position to tip over changes from the side of main tracks to the left or right flippers.

The application of the S_{NE} graph for stability on the roll direction is explained as follows. When we assume a stability margin as the 30 percent of S_{NE} in case that the robot stays at the horizontal plane, the margin of S_{NE} is 0.06 meters in the roll direction. Therefore, we can define a stable area in the graph shown in Fig. 9 to be $S_{NE} > 0.06$ meters. If the condition of the robot locates out of this area, it should stop moving motion and abort its task to avoid tipping over.

V. EXPERIMENTS

We implemented the proposed strategy of an autonomous flippers motion control shown in section 3, and performed

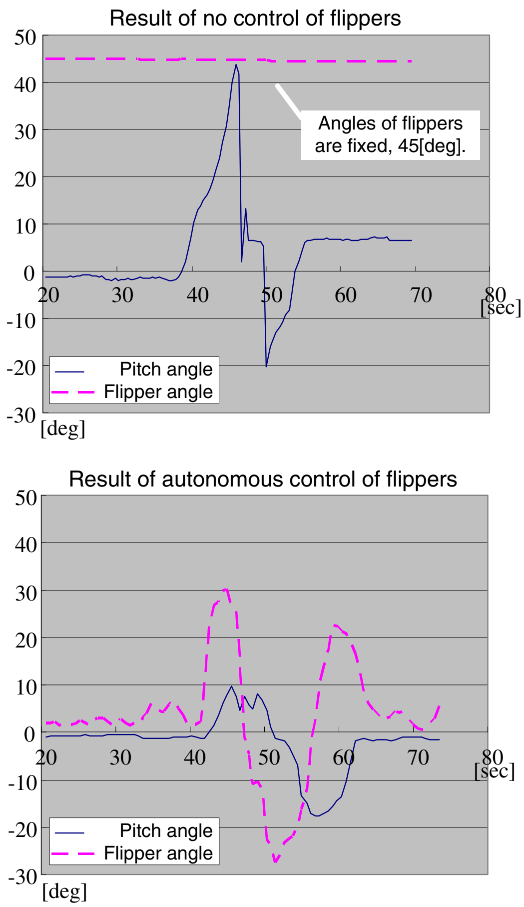

Fig. 10. Results of Exp-1, with and without proposed autonomous control

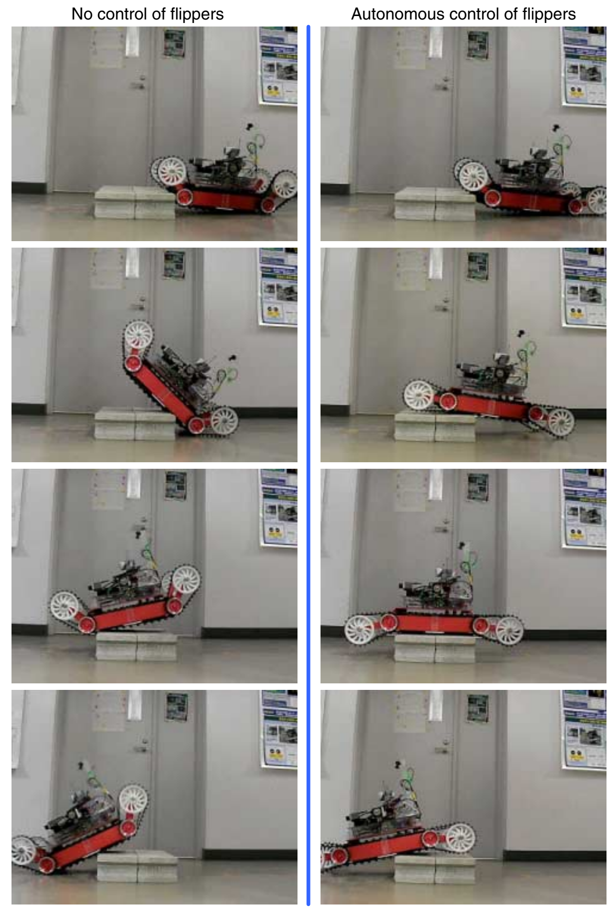

Fig. 11. A Series of photographs in Exp-1

several experiments. Simple steps and a simulated disaster environment was built by concrete blocks. Each block has a length of 32 centimeters, a width of 19 centimeters, and a height of 12 centimeters.

A. Exp-1: a single step for both flippers

The first experiment was performed inside a simple environment; set of four concrete blocks was used as a single step. The height of the step is 12 centimeters. The robot was located at a suitable place so that both flippers touched the step by simple moving forward. The operator sets the robot's speed to 60 millimeters per second. In the experiment we set two upper limits as $\theta_{pmax} = 5$ degrees and $\theta_{rmax} = 5$ degrees. For practical purposes, both values can be larger because, as shown in the previous section, the stability analysis was derived that the θ_{pmax} could be larger, increasing the maximum height of the surmountable step. However, in this experiment, to confirm the validity of our stability approach, we set the two limits in such small values.

Fig. 10 shows two results of the robot's pitch angle and its left-front flipper angle with and without autonomous control of the flippers. In case that there is no control of the flippers, the flipper angles were fixed as 45 degrees. In the result, the pitch angle of the body was increased to almost 45 degrees with no-control. On the other hand, in the case of the autonomous control of the flippers, the pitch angle was suppressed to less than 20 degrees. Left-front flipper angle was controlled as tracing a dotted line. Comparison of both graphs is a good example to verify the advantage of our strategy. Furthermore, Fig. 11 shows two series of robot's motions, corresponding to the above graphs. In a series of photographs where no control was used, the robot came near to tip over.

B. Exp-2: a single step for right flipper

The second experiment was performed in the same environment as Exp-1. However, the robot was located at a suitable place initially so that the right flipper only could touch the step when the robot was moving forward. The speed and the upper limit values of θ_{pmax} and θ_{rmax} were set to the same values as in Exp-1.

Fig.12 shows a comparison between roll angles with and without autonomous control of the flippers. According to this graph, the roll angle of the body became more than 20 degrees without autonomous control of flippers. The bottom-left photograph in Fig.12 shows this situation. On the other hand, the maximum roll angle of the body was almost 5 degrees with autonomous control of flippers although the behavior of this value was not completely constant. The bottom-right photograph in Fig.12 shows one scene of this

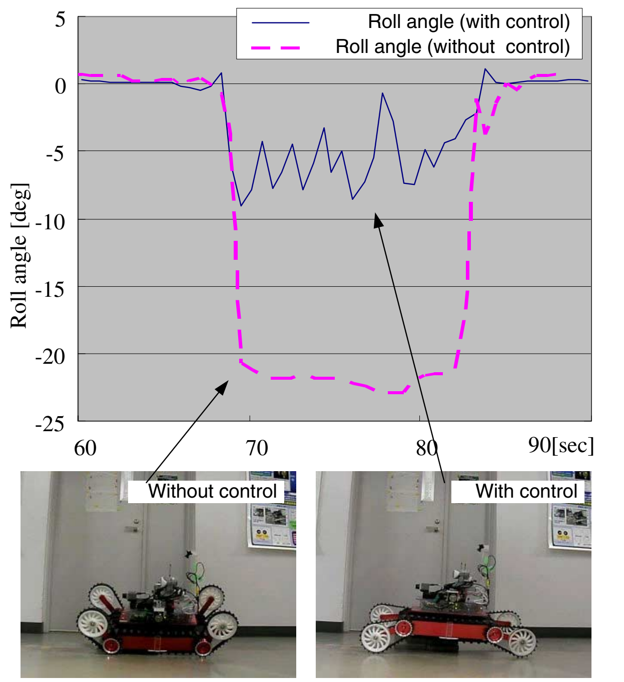

Fig. 12. Results of Exp-2, with and without proposed autonomous control

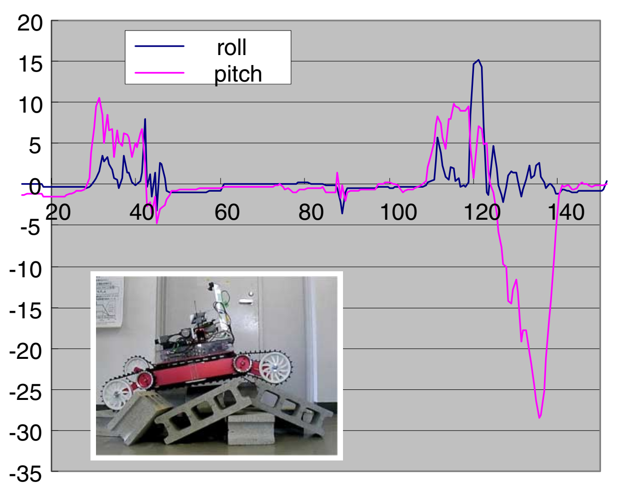

Fig. 13. Results of Exp-3, roll and pitch angles for tracked vehicle while it traverses the blocks

situation. Left-flippers rotated towards the ground to keep body angle stable. Based on the result, the roll stability performed accordingly to our proposed strategy.

C. Exp-3: simulated disaster environment

The third experiment was performed in a more robust environment, where several concrete blocks are piled up randomly. The robot's speed was the same as experiment 1, and the upper limit values were set as $\theta_{pmax} = 15$ degrees, and $\theta_{rmax} = 15$ degrees.

The upside of Fig. 13 depicts the behavior of the roll angle and pitch angle of the body. This graph shows that a large pitch angle was generated while the robot went down from the blocks at the end of the experiment. However, for the rest of its motion, the maximum pitch angle of the body remained less than 10 degrees because of autonomous control of flippers. Fig. 13 shows one scene that the robot traversed on a complicate environment. Finally, the tracked vehicle completed traversing such a complicated uneven terrain.

VI. CONCLUSIONS AND FUTURE WORKS

In this research, we proposed a strategy of autonomous motion of flippers for tracked vehicles to enable semi-autonomous traversal on uneven terrain. One of the big features is the use of laser range sensors for terrain sensing to control flippers' angles autonomously. This method was successfully implemented in our tracked vehicle, and the robot performed very robust motions in real complicate environments, even though the proposed algorithm is very simple.

We also performed a stability analysis of such tracked vehicles based on "static stability criterion". This analysis gives us a knowledge of angle-margins (roll and pitch) not to tipping-over of such robots. In our current implementation, S_{NE} is used just as an alarm of tipping-over of the robot.

Among the possible future work to be performed, we would like to verify if more intelligent control is effective or not. Laser range sensors can acquire the shape of the ground. However in this research, we use only the highest measured point to determine the flipper angles. There might be better control methods to use knowledge of the shape of the environment. Stability estimation in near future is another important issue. There is a possibility to guess a stability of near future of robot's posture using range sensors.

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