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Real-Time Recognition of the Terrain Configuration to Improve Driving Stability for Unmanned Robots

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Abstract**—**Methods for measuring or estimating ground shape by a laser range finder and a vision sensor (Exteroceptive sensors) have critical weaknesses in terms that these methods need a prior database built to distinguish acquired data as unique surface conditions for driving. Also, ground information by Exteroceptive sensors does not reflect the deflection of ground surface caused by the movement of UGVs. Therefore, this paper proposes a method of recognizing exact and precise ground shape using an Inertial Measurement Unit (IMU) as a proprioceptive sensor. In this paper, firstly this method recognizes the attitude of a robot in real-time using IMU and compensates attitude data of a robot with angle errors through analysis of vehicle dynamics. This method is verified by outdoor driving experiments of a real mobile robot.

Keywords**—**Inertial Measurement Unit, Laser Range Finder, Real-time recognition of the ground shape.

I. Introduction

IT is essential for Unmanned Ground Vehicles (UGV) to run autonomously on possible driving areas with the global path planning. Therefore, many researchers proposed various methods for determining the possible driving area with many types of information such as colored data and distance data from vision sensors and Laser Range Finder (LRF), respectively [1], [2]. Additionally, there are many resources to build maps in 3-dimensionsincluding sensor fusion by vision sensor, LRF, GPS and IMU etc. [3], [4].

A 3D world model is generally employed to plan a safe path for UGVs. If start and end points are given, UGVs can plan an optimized path regarding energy efficiency or maneuverability using an algorithm like ‘Dynamic A*’ [5]. Most research in non-contact recognition methods are based on recognizing surroundings which are far away from the robot. In other words, it recognizes the flection of terrain and distinguishes obstacles beforehand. However, it is not enough for UGV to assure driving stability. Since the vision sensor and the LRF cannot measure slip ratio, they do not reflect the sinkage of ground surface. Geological characteristics such as slip ratio and sinkage of ground surface are important variables to enhance the driving stability and efficiency of UGV. So, many researchers have already presented the various methods to classify geological characteristics and drive efficiently according to geological characteristics [6]-[14]. Thus, the data obtained from the laser sensor and image sensor may be defined as *data of the prediction* of the environment which the robot has not experienced directly. Depending on what information has been previously learned, the driving performance of autonomous robots is determined. Therefore, in order to improve the driving stability of the robot, it requires much more learned information. However on rough terrains, it is not easy to acquire environmental information because there are a lot of unpredictable environmental variables. Therefore even when building the database learned by considering the variables in all situations, it requires algorithms for enhancing abilities of recognition by acquired data.

On the other hand, *empirical data* may be defined as the data obtained near the body of the robot through actual driving of the robots. The empirical data has the environmental information of a smaller range than the data of the prediction, but its reliability is relatively high because that data is obtained from the substantial experience. In previous studies, it determined the geological characteristics of the prior region on the basis of data that has been learned in advance from the image sensor, and it updated the actual geological characteristics from the data of the vibration sensor attached to the wheels. On the basis of these studies it is possible to create a geological map of the preceding area. Likewise, the studies utilizing the contact-type sensor has been advanced as a matter purpose for determining the geological characteristics. Furthermore, the research for recognizing the ground shape is dependent on the image sensor and the laser range finder and its purpose is to increase the accuracy of the prior terrain recognition by fusing sensors [2]-[11].

In this paper, we propose a method for recognizing the ground shape based on the data that is experienced through the IMU attached to the robot. To estimate the posture of the UGV in contact with the ground makes it possible to determine the driving stability of the UGV in real-time by recognizing the gradient of the ground. Thus, it drives along the path that has been planned in the 3D world model that is generated based on the data of the prediction, and it corrects in real time the shape information of the contact ground. Thereby, it makes possible the increased driving stability of the autonomous robot.

II. The Method of Recognition to Contacted Terrain

A. Compensation of Pitch angle Applying Robot Dynamics

In order to recognize a more accurate ground shape, it is necessary to get a correct angle by applying a kinetic analysis.

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The dynamic equation described in this paper was built based on the robot used in the experiment. Therefore, in order to compensate for the angle kinetic analysis is applied to suit each robot. The robot used in the experiment is a four-wheel drive robot with no steering device. So, it affects the IMU to include two noises. First, since there is no suspension system designed, generated vibration from driving is passed directly to the IMU, which can act as noise. Further, the spring damper system that acts on the tire should also be considered. The load difference that acted on the front wheels and the rear wheels occur between the angle of contact and the driving acceleration of the robot. If the robot drives on the road, such as a flat terrain in constant velocity, the acceleration is zero (a = 0). So, a load applied to the front wheels and the rear wheels is almost the same and the angle error due to the difference of the load is hardly generated. On the other hand, when the robot drives in accelerated motion and drives on downhill and uphill terrain, it makes a difference in the load of the front wheels and that of the rear wheels, resulting in the body of the robot becoming inclined. However, the IMU which is connected to the body of the robot is not able to distinguish the inclination due to the difference in load on each wheel. Therefore, it is necessary to remove by classifying the angular error in accordance to the load by applying a simple dynamic analysis to the angle data measured from the IMU.

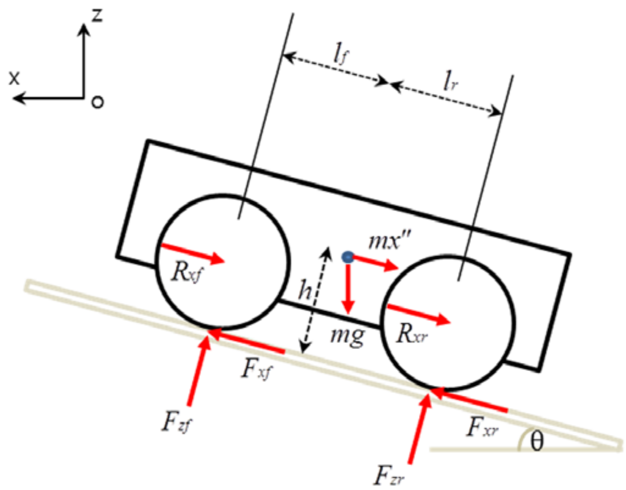


Fig. 1 The force acting on each wheel

Fig. 1 is showing the forces acting on each part of the robot. Air resistance was excluded on the assumption that is not significantly affected. The moment on the basis of each wheel is expressed as (1) and (2). First, in order to correct the angle error caused by the acceleration, it is assumed that the angle of the terrain is 0 degrees. And then, (3) and (4) can be summarized as a load applied to the wheels by (1) and (2). Load value of each wheel (F_{zf}, F_{zr}) which calculated in each sampling time can be calculated by the displacement value which the tire was pressed by substituting it in the F_T(The force applied to the tire) of (5). The angle data due to the difference of the displacement values between the front wheels and the rear wheels is defined as inertial angular error by the driving acceleration of the robot, and subtracted from actual data measured by the IMU. But, the thing to note here is finding value of the k that is the stiffness coefficient of the tire. The k must be considered both the deformation of non-linear and the deformation of linear. However, in this paper, assume that the stiffness will increase linearly in accordance to the pressure applied to the tire, and the changed stiffness coefficient depending on the load value that is obtained in the sampling time.

Second, the load applied to each wheel of the robot is influenced by not only the acceleration but also the angle of the terrain. Accordingly, the additional angle correction should be made in accordance with the angle of the shape of the ground. Therefore, remove the section that contains the acceleration of (1) and (2), and express the load corresponding to the angle of the terrain by (6) and (7). The load value obtained is calculated with the displacement values of the tire that was pressed by substituting in the F_T of (5). So, the angle error by differences of displacement values of the tire that obtained in this process, are defined as the angle error that correspond to terrain angle, and subtracted from the data after 1st angle correction process.

$$F_{zf}(l_f + l_r) + m\ddot{x}h + mgh\sin\theta - mgl_r\cos\theta = 0 \tag{1}$$

$$F_{zr}(l_f + l_r) - m\ddot{x}h - mgh\sin\theta - mgl_r\cos\theta = 0 \tag{2}$$

$$F_{zf} = \frac{mgl_r - m\ddot{x}h}{l_f + l_r} \tag{3}$$

$$F_{zr} = \frac{mgl_f + m\ddot{x}h}{l_f + l_r} \tag{4}$$

$$F_T = kz \tag{5}$$

$$F_{zf} = \frac{-mgh\sin\theta + mgl_r\cos\theta}{l_f + l_r} \tag{6}$$

$$F_{zr} = \frac{mgh\sin\theta + mgl_f\cos\theta}{l_f + l_r} \tag{7}$$

B. The Method of Ground Shape Recognition

In order to recognize the ground shape by using the data from experience, the absolute speed of the robot and the angle data where the robot is in contact with the ground is required. The angle data is used, estimating the height and bend of the ground, and the absolute speed data is used to estimate the moving distance and the moving direction of the robot. First, the angle data outputted from the IMU is data that is outputted on the basis of the body of the robot. Therefore, in order to display the angle data in real time at the global coordinate, it is necessary to transform the coordinate using the rotation matrix. If the angle data is multiplied with one of the Euler's rotation matrix (represented by 'Yaw-Pitch-Roll'), it can be converted to global coordinates. Further, by adding the data of moving distance of the robot, it is possible to display the movement and posture of the robot in the global coordinates, which is expressed by (8). The 3x3 matrix indicates the rotation matrix that is multiplied with $\vec{R}$. In this paper, the center coordinate of the robot fixed of a constant on the assumption that it has a rigid body, and d_x is the value of the position obtained from the absolute velocity meter. Further, the experiment is progressed by straight driving in the x-axis direction, there is no motion in the y-axis direction of the robot, so, it has been assigned 0 to $d_y(d_y = 0)$. The d_z is the height which was calculated by defining the length of the hypotenuse to the displacement in the x-axis direction (d_x–d_{x-1}) that was obtained from the absolute velocity meter, and defining the slope of the hypotenuse angle values that were obtained from IMU.

The value of the angle corrected by the dynamic analysis is respectively inputted in the φ, θ, ψ in (8). Because it was an experiment to confirm the movement of the θ, it did not apply a dynamic compensation in φ, ψ.

$$\begin{bmatrix} R_x' \\ R_y' \\ R_z' \end{bmatrix} = \begin{bmatrix} C\phi C\theta & C\phi S\theta S\psi - S\phi C\psi & C\phi S\theta C\psi + S\phi S\psi \\ S\phi C\theta & S\phi S\theta S\psi + C\phi C\psi & S\phi S\theta C\psi - C\phi S\psi \\ -S\theta & C\theta S\psi & C\theta C\psi \end{bmatrix} \begin{bmatrix} R_x \\ R_y \\ R_z \end{bmatrix} + \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} \quad (8)$$

$\vec{R}'$: Center coordinates of the robot body in the global coordinates

$\vec{R}$: Center coordinates of the robot body in the local coordinates

$\vec{d}$: A moving distance of the three axial directions

φ : Yaw θ : Pitch ψ : Roll

The value of the angle corrected by the dynamic analysis is respectively inputted in the φ, θ, ψin (8). Because it was an experiment to confirm the movement of the θ, it did not apply a dynamic compensation in φ, ψ.

III. Construction of the Robot System and Decision of the Experimental Places

A. Robot System

While there is no steering system, the robot of in Fig. 2 that was used in this paper is a four-wheel drive and skid type. The overall size of the robot is 49 × 65 × 32cm. At the center of the body of the robot, an IMU is attached. The total weight including the system unit and the sensor is 16kg. The wheels of each connected DC motor, available with independent control, and the maximum speed is about 2m/s. It has additional wheels designed for measuring the absolute speed of the robot in the rear of the robot, since there are no motors on the wheels, which are just connected to the encoder. Thus, even if each wheel slipped, they can estimate the absolute speed of the robot.

The control of the robot is based on the PID control. The output period of the angle data that is output from the IMU is 80Hz, the sampling time of the entire system is 0.05s. Also, it is given 3 seconds as the waiting time of force immediately after the operation of the system by considering the stabilization time of all sensors, and data output from the sensor can be stored when the robot moving, but does not save the data anymore if the robot stops driving.

Fig. 2 The robot model

Initialization of the IMU must be progressed during the forced waiting time to measure accurately the position and the moving direction of the robot. TheIMU estimates the Yaw value through a geomagnetic sensor. So, subtract the average value obtained by receiving data samples from the initial stop state from the data output after. As a result, Yaw value was zero as always (Yaw = 0°). In the same way, making the Pitch and Roll 0 can be selected according to the experimental environment.

B. Experimental Places

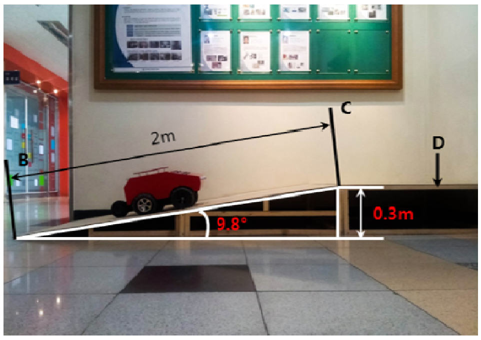


Fig. 3 Experiment in reference structures

For initial experiments, a reference terrain structure is made where the length of the hypotenuse is about 2m, and height is about 0.3m, and tilt is about 9.8 degrees as shown in Fig. 3. Through the experiment, it is possible to confirm the factors that influence the data output from the IMU, and confirm the performance of the ground shape recognition algorithm by applying the angle compensate algorithm. In addition, two outdoor experimental places were selected. One is uphill terrain, and the other is bump terrain in Fig. 4, the robot was driving at the speed of 0.5m/s and 1m/s to verify the angle compensation algorithm. It was decided that the starting position of the robot in the experiment in each place, would be flat terrain.

For the uphill terrain, the slope of the hill is about 7.4 degrees, the length is 2.8m and the height is about 26cm. Unlike the reference structure, it is rough and not smooth. For the bump terrain, the slope is about 8 degrees uphill and downhill and the height is about 8cm.

Fig. 4 Experimental Places - Uphill and Bump terrain

IV. Analysis of Experimental Results

A. Analysis of the Results from Each Experimental Setting

1. In the Case of Reference Structures

Fig. 5 is a graph of the acceleration data obtained by driving on the reference terrain structures at the speed of 0.5m/s and 1m/s. It shows that the acceleration value is larger in sections A-D and A'-D'. Section A and A' is the output value by the initial acceleration of the robot, and B, B' shows the output that the value of the acceleration of the robot when reduced by the impact that occurs when meeting the hill. The C and C' sections show acceleration due to the decrease of the load at the moment after finishing the drive on the hill, while D and D' are confirmed to be the output of the data when the robot stops. By acting as an inertial force, sudden acceleration in all sections presented generates a displacement difference between the front and rear wheels of the robot. Slope due to the displacement difference of the tire, is able to have a direct impact on the IMU attached to the body of the robot, and cannot output the exact angle of the ground in contact with the robot. Therefore, as described in the previous section, calculating the angular error due to the acceleration is necessary to compensate for this.

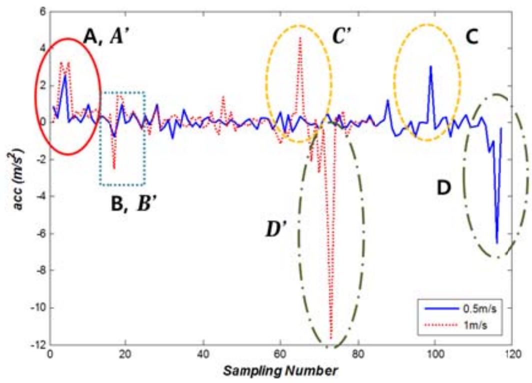


Fig. 5 Changing of acceleration when driving in the reference structure

Fig. 6 is showing the comparison results before and after applying the angular compensation to the angle data obtained by driving on a reference terrain at the speed of 0.5m/s. The calculated height of the terrain before compensation of the angle is approximately 31.5cm, and it ensures that there was an error of approximately 1.5cm from the value of the actual height, the cause was assumed to be the inertial angular error due to acceleration of an early drive. Actually, the robot first drives at a constant interval on flatland, but it is difficult to distinguish that from the angle data before compensation in Fig. 6. It rather appears as if it is driving on uphill terrain. The reason for this is caused by the acceleration of the robot when driving, and the initial angle of the inertial measurement unit whose output is about 4 degrees momentarily. For this reason, when determining the d_z, error occurs. As a result, the value of the height that is output after applying the angle compensation is almost the same height with the actual terrain, and it was possible to distinguish the section of flatland driving early.

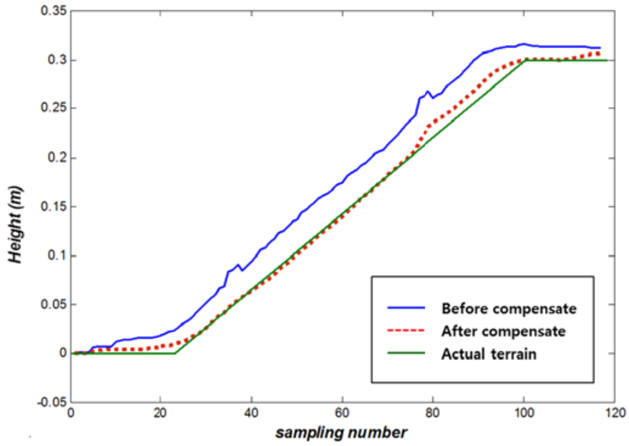
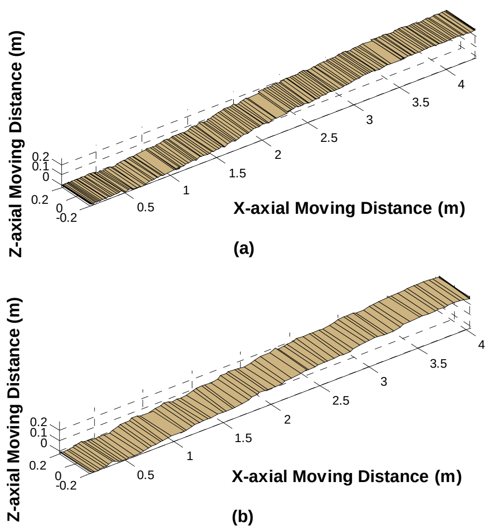


Fig. 6 Comparison of the results before and after applying the angular compensation

2. In the Case of Uphill Terrain

Fig.7 is displayed by using the obtained data from changing the driving speed of the robot on MATLAB. Based on the center coordinate of the robot in the global coordinates obtained by (8), it made the form of a patch where the robot is in contact with the ground. The height of the terrain is recognized more accurately in accordance to the increasing speed of the robot, but it could be compensated by using the angle compensation algorithm.



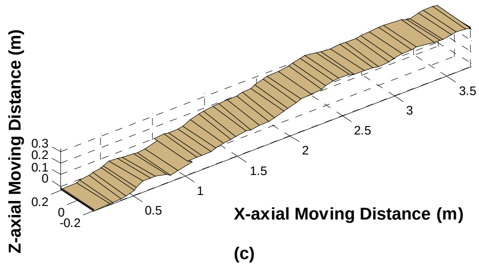


Fig. 7 Recognition results of the uphill terrain on the speed (a) 0.5m/s, (b) 1m/s, (c) 1.5m/s

Fig. 8 is the compared results of the data obtained by driving at the speed of 0.5m/s and 1m/s in the uphill terrain. The value of the height that is calculated before applying angle correction of the whole, appears greater than the height of the actual terrain, it can expected to be the result which is the angle error due to the driving acceleration and the slope of the terrain. Thus, calculating each error and subtracting it from the angle values measured from IMU, it is then possible to recognize the ground shape from contact with the ground through (8).

Fig. 8, the analysis results of the data obtained by driving at the speed of 0.5 m/s, shows that the value of height was 31.78cm before compensation, but it calculated 26.39cm by applying the compensation, which is closer to the terrain's actual height. As a result of analyzing more than 30-sampled data was approximately 0.5 in error on average less than the height of the actual terrain. On the other hand, the data obtained by driving at the speed of 1m/s has an error of about 3cm though applying the algorithm to compensate for the angle. The reason was determined that, the characteristic of the uphill terrain has more roughness than the reference structures.

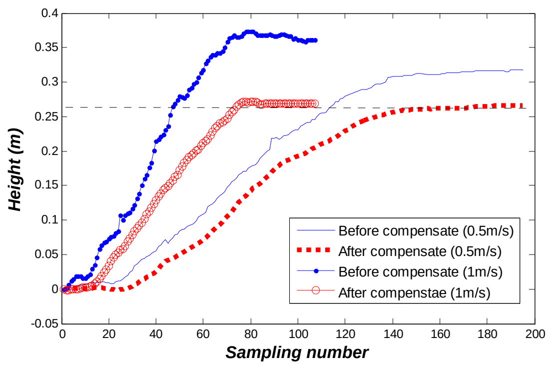


Fig. 8 Comparing height of recognized terrain before and after compensate angle in uphill terrain

3. In Case of Bump Terrain

Fig. 10 is the compared results of the experiment data on the bump terrain. The estimated shape of the ground using the data obtained by driving at the speed of 0.5m/s was relatively accurate as a result of the uphill terrain. However, Fig. 9 shows the data obtained by driving at the speed of 1m/s, but estimating the shape of the ground was difficult. In fact, when driving at the speed of 1m/s the robot jumped from the ground. At that moment, the obtained angle could not be used as data for recognition of the ground shape, and an additional disturbance occurred, caused by secondary impact. Therefore, it was difficult to recognize the contacted ground using the method of compensation of the angle proposed in this paper when the robot jumped from the ground.

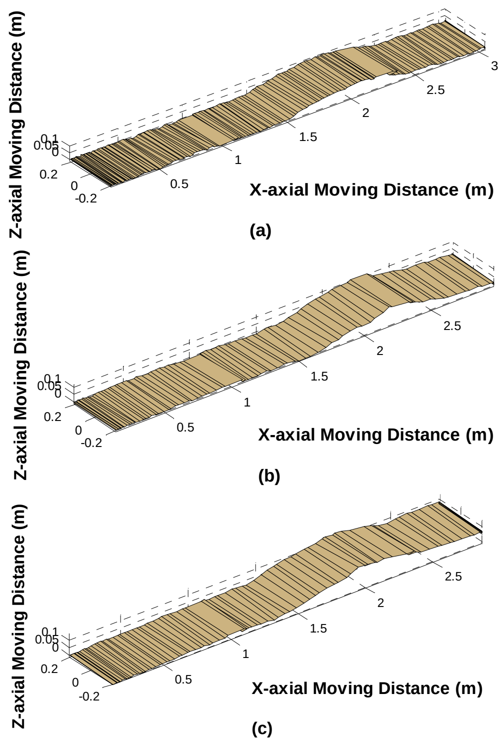


Fig. 9 Recognition results of the bump on the speed (a) 0.5m/s, (b) 1m/s, (c) 1.5m/s

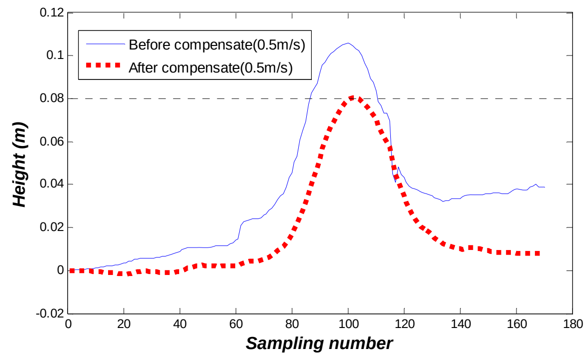


Fig. 10 Comparing height of recognized terrain before and after compensate angle in bump terrain

B. Review of the Experimental Results

The results of experiments on outdoor terrain, uphill terrain and bump terrain based on the results of experiments of the reference terrain structure shows generally very similar information to actual terrain at low speed, since the disturbance is low. However, the faster the speed, the more difficult it is to recognize the ground shape. This is because of the noise is increasing proportional to the speed, as well as the dynamical variables that cannot be predicted.

V. Conclusion

This study is the basis research to compensate the 3D world model made from the data by image sensors and LRF, and its purpose is updating the accurate information of the ground shape. If the robot is driving at low speeds it could confirm that recognizing the ground shape accurately by applying that proposed angle compensation algorithm. However, the dynamical structure of the robot that will be applied in this system does not match with the other, and the recognition error is greater according to the speed. In particular, the speed increases, and there are many unpredictable variables to compensate for the kinetic equation which is difficult to establish. Thus, there is almost no impact on the speed and no effect on the dynamical structure of different robots which aim to develop algorithms.

References

[1] D. Kim, J. Sun, S.M. Oh, J. M. Rehg, and A. Bobick, "Traversability classification using unsupervised on-line visual learning for outdoor robot navigation" *IEEE Intl. Conf. on Robotics and Automation*, pp. 518-528, May 2006.
[2] Tae Won Kim, Jin Hyoung Kim, Sung Soo Kim, Yun Ho Ko, "Land Preview System Using Laser Range Finder based on Heave Estimation", *Journal of Electronics Engineering*, vol. 49, pp. 63-73, no. 1, 2012.
[3] Ji Hoon Joung, Kwang Ho An, Jung Won Kang, Woo Hyun Kim, Myung Jin Chung, "3D Terrain Reconstruction Using 2D Laser Range Finder and Camera Based on Cubic Grid for UGV Navigation", *Journal of Electronics Engineering*, vol. 45, pp.26-34, no. 6, 2008.
[4] Sijong Kim, Jungwon Kang, Yungeun Choe, Sang Un Park, Inwook Shim, Seunguk Ahn, Myung Jin Chung, "The Development of Sensor System and 3D World Modeling for Autonomous Vehicle", *Journal of Automation and Control Engineering*, vol. 17, pp.531-538, no.6, 2011.
[5] A. Stentz, "Optimal and Efficient Path Planning for Partially-known Environments", *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 4, pp. 3310-3317, May 1994.
[6] Byoung-gon Park, Jayoung Kim, Jihong Lee, "Terrain Feature Extraction and Classification using Contact Sensor Data", *Journal of Korea Robotics Society*, vol. 7, pp. 171-181, no. 3, 2012.
[7] Jayoung Kim, Jihong Lee, "Predicting Maximum Traction to Improve Maneuverability for Autonomous Mobile Robots on Rough Terrain", *Journal of Automation and Control Engineering*, vol.1, no.1, 2013.
[8] Jayoung Kim, Jihong Lee, "Prediction of Maneuverability and Efficiency for a Mobile Robot on Rough Terrain through the development of a Testbed for Analysis of Robot-terrain Interaction", *Journal of Korea Robotics Society*, vol. 8, no. 2, pp. 116-128,2013.
[9] Christopher A. Brooks, Karl Iagnemma "Self-supervised terrain classification for planetary surface exploration rovers", *Journal of Field Robotics*, vol.39, no. 1, 2012.
[10] Byunggon Park, Jonghwa Lee, Jayoung Kim, Jihong Lee, "Classification of terrains by body motion and contact force", *Institute of Electronics Engineering*, June 2010.
[11] Dupont, E.M, Moore, C.A., Collins, E.G., Jr., Coyle, E., "Frequency response method for terrain classification in autonomous ground vehicles", *Autonomous Robots* 24.4,2008.
[12] Sang Hyun Joo, Jihong Lee, "A Dynamic Modeling of 6×6 Skid Type Vehicle for Real Time Traversability Analysis over Curved Driving Path" *Journal of Automation and Control Engineering*, vol.18, pp.369-364, no.4, 2012.
[13] Sang Hyun Joo, Jihong Lee, "A High-speed Autonomous Navigation Based on Real Time Traversability for 6×6 Skid Vehicle", *Journal of Automation and Control Engineering*, no.3, 2012.
[14] Doo-gyu Kim, Ja-young Kim, Jihong Lee, Dong-Geol Choi, In-So Kweon, "Utilizing Visual Information for Non-contact Predicting Method of Friction Coefficient", *Journal of Electronics Engineering*, vol. 47, pp. 28-34, no. 4, 2013.

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