The Design, Fabrication and Preliminary Testing of a Variable Configuration Mobile Robot

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Abstract: In this paper a novel low cost mobile robot that can adjust the balance between the energy efficiency and the running performance according to the environment by changing the number of wheels is introduced. The developed robot, which can be constructed by combining the modules and is driven by Robot Operating System (ROS) tools, has a 3D light detection and distance measurement (LiDAR) for generation of 3D digital map and travels through several environment with saving the energy by adaptively changing the number and arrangement of the wheels according to the environment. The robot can easily change the three types of mechanisms by changing the number of modularized driving wheels and their combination. Furthermore, the developed robot can construct a 3D map in a rough outdoor environment and the running performance of three kinds of robots was investigated by an extensive characterization. Finally, the limits of this prototype have been meticulously analyzed, highlighting new improvements in the future perspective development for permitting an autonomous environment perception with a simple, modular and low-cost device.

Keywords: Mobile robot, driving module, 3D digital map, LiDAR, ROS.

1. INTRODUCTION

In order to cut trees in forestry, it is necessary to measure the number of trees and predict profits, plan the entry route of heavy machinery into the cut down area, and to design the conveying route of logged trees [1]. Therefore, it is necessary to measure the forest environment in detail before these works. Various situations exist on the ground of the forest, and fallen leaves, weeds, deciduous trees, etc. are usually falling. In the forest, it is difficult to identify the position by Global Navigation Satellite System (GNSS) signals due to the influence of trees, so the generation of three dimensional digital map by light detection and distance measurement (LiDAR) has been studied [2, 3]. However, the time that an engineer can work for this measurement work is limited by the weather and work period, so it is expected that this work will be automated.

Various attempts have been made to automate the measurement of forest environment so far. With experience in using two-dimensional (2D) LiDAR for measuring logs, work on modeling of the trees and forest on the basis of laser scanners has been performed since the 1990s [4]. Currently, research based on the application of Simultaneous Localization And Mapping (SLAM) is widely conducted. In addition, several methods of measuring standing trees using 2D LiDAR [5, 6] have been proposed, and several four-wheeled mobile robots that installs these algorithms and generate digital maps with real-time SLAM using GPS and multiple three-dimensional (3D) LiDARs have been developed. In addition, Unmanned Aerial Vehicle (UAV) equipped with LiDAR [7] and measurement by a six-wheeled robot having a rocker bogie mechanism have been developed and their performance has been experimented [8].

On the other hand, it is difficult to predetermine the mechanism and size of mobile robots suitable for various environments and tasks. In each forest environment, growth degree and density of the plant, kind and size of weed growing on the ground, heterogeneity of the ground, aspects of the ground surface, and so on are different. Increasing the contact area by increasing the number of wheels improves the running performance of the robot but reduces the energy efficiency for the movement. Reduction of energy efficiency should be avoided in designing autonomous mobile robots that must carry limited energy sources. Namely, there is a trade-off relationship between the number of wheels and the running energy. If it is a relatively flat ground, a robot can travel sufficiently with an independent two-wheel mechanism and has high energy efficiency. For traveling on a rough meadow, running performance can be improved by running on four or more wheels. In addition, in the case of driving in the forest and sand, a six-wheel rocker bogie mechanism for ensuring runnability is suitable, however its energy efficiency is low [9].

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Recent works [10-11] have highlighted that robot operating system (ROS) platform is particularly advantageous for environment mapping generation by using a LiDAR mounted on a mobile robot. Moreover, the possibility of using the LiDAR data (point cloud data) with efficient algorithms for simultaneous robot localization and mapping has also been recently demonstrated (i.e. [12]). Therefore, in this research, a novel low-cost robot driven by ROS and realized with modularized wheel and a frame for connecting them and for supporting a scanning LiDAR is presented with an extensive characterization of its performance in relation with the LiDAR vibrations respect to the type of surface with which robot is in contact. This is very important because the 3d LiDAR sensor mounted on the robot depending on the vibrations acting on the system, can scan the surrounding environment more efficiently with lower oscillations by using recent algorithms introduced in literature. The tests on the repeatability of the data and the analysis of the noise produced have been extensively carried out for determining the accuracy of the accelerometer mounted inside. Finally, a specific research was carried out to lay down the robot's batteries autonomy in relation to the wheels configuration used in order to be able to adjust the balance between the robot's run ability and energy efficiency according to the environment. The developed robot, which can be constructed by combining the modules, can adaptively change the number and arrangement of the wheels according to the environment to be measured and by taking into account the results of the present research.

2. DESIGN OF ROBOT AND FEATURES

2.1. Devices of Robot

In order to control the robot, one laptop computer with Intel Core m5 (1.10 GHz) and Ubuntu 14.04 LTS has been used. In addition, the robot operation system (ROS) [13] was adopted as middleware. Then, the following devices were incorporated into the robot: motor driver (MDD10A) which generates PWM signal, a motor controller (iMCs01) including pulse counter, a 3D LiDAR (YVT-X002, Hokuyo), and a 24 V battery. The robot system diagram is shown Figure **1**. It is possible to control two driving modules with a set of motor driver and motor controller by a signal from the laptop with USB connection. The LiDAR uses power directly from a 24 V battery.

2.2. Frame of Robot

The frame of the robot is designed so that the number of drive wheels can be changed according to the environment where the robot is traveling. Depending on the environment, the robot can be easily changed by user to two energy-efficient wheel versions, six wheel versions with high running ability against complicated terrain, or four wheel versions with intermediate capabilities of them. Therefore, by designing the frame as an x shape as shown in Figure **2a**, since the width and length of the robot are the same, the robot can execute a spin turn by reverse rotation of each wheel. In the two wheels version, two

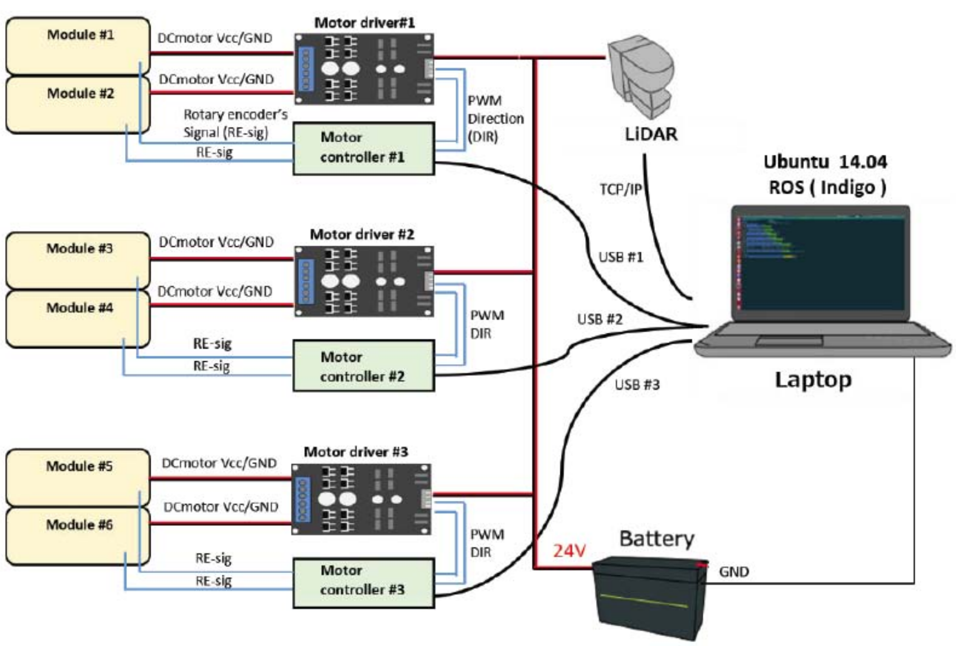
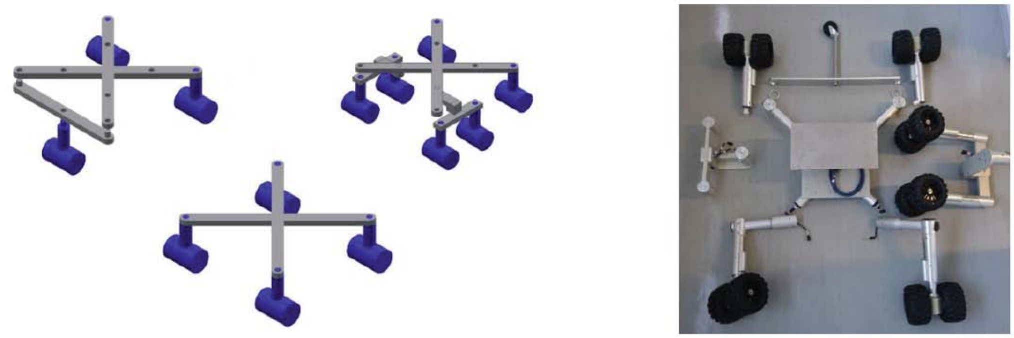


Figure 1: Signal and electric diagram of developed robot system.



(a) Designed frames for changing the number of driving wheels. (b) Developed frames and driving modules.

Figure 2: Combination of the driving modules with developed frames.

driving wheels and one slave wheel are used. In the four wheels version, four driving wheels are connected in the same direction to the frame. In addition, for the six wheels version, an attachment frame was developed so that it becomes a rocker bogie mechanism. The proposed driving wheels, the frame, and the attachment frame are shown in Figure **2b**.

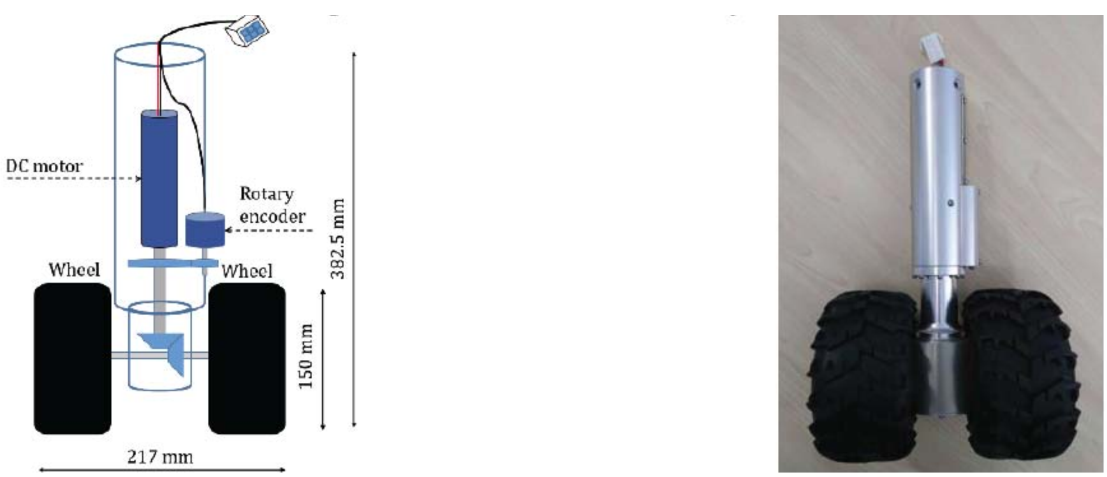
2.3. Driving Module

The driving module, shown Figure **3**, consists of a DC motor (TE-38F16-24-64), a rotary encoder (E6A2-CW3E), and two wheels connected shaft and gears. The total length is 382.5 mm, the total width is 217 mm, and the weight is 2500 g. The wheel's diameter is 150 mm and the maximum velocity is 0.4 m/s. This module has waterproof performance. Also, by equipping two tires in parallel, the driving module became less likely to catch on weeds and branches while the robot was moving. After connecting the connectors of each module and the frame, fix it by screwing with the frame. By measuring the rotation angle of the tire with a rotary encoder, the rotation speed of the tire is controlled. Also, since the sponges are inside the tires, they do not puncture [14].

2.4. Configuration of the Robot

The developed robot can be changed to three different configurations by changing the combination of drive modules as shown in Figure **4**. The first type consists of six driving modules and two rocker bogie joint attachment. The second one has four driving wheels, the third type has two driving wheels and one non-driving wheel. Each types are designed depending on an assuming following fields.

- The six-wheel type: this is for traveling across all different conditions of the road (mud, grass, asphalt) and can climb obstacles [15]. This is



(a) Structure. (b) Over view.

Figure 3: The driving module consists of a DC motor, a rotary encoder, four gears and two wheels. (**a**) Structure and (**b**) over view of a driving module.

(a) Two-wheel type. (b) Four-wheel type. (c) Six-wheel type.

Figure 4: Three types of the robot configuration with changing drive wheel combinations; (**a**) two-wheel type with one non-driving wheel, (**b**) four-wheel type, and (**c**) six-wheel type with rocker bogie joint attachment.

influenced by the Rocker-bogie mechanism [16-18]. These characteristics are perfect to drive the Robot trough forest environment.

- The four-wheel type: this keeps a great stability during up-hill and cross-hill, because of its symmetrical body, anyway the Robot presents some problems to climb obstacles due to no-bogie joint and no flexible structure.
- The two-wheel type: this is the simplest configuration; Robot has a good stability but risks to tip over the ground if it overcomes obstacles or travels across rough ground.

3. EXPERIMENTS

3.1. Generating a Digital 3D Map

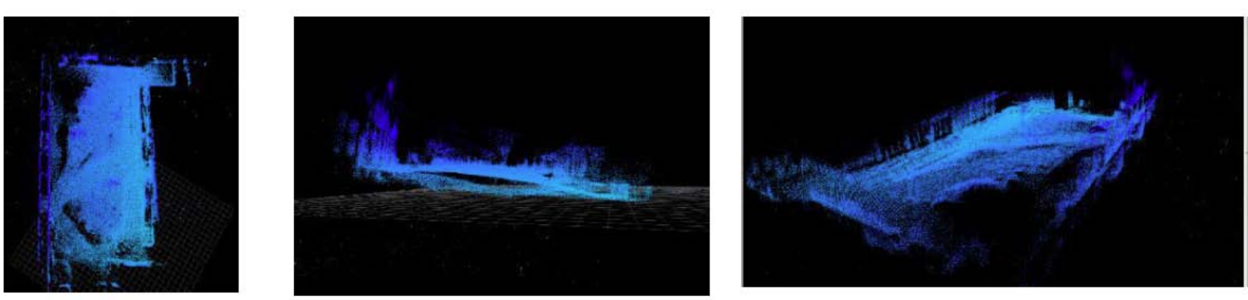
In order to confirm the performance of the robot, we executed a 3D digital map generation experiments using the normal distributions transform (NDT) SLAM algorithm [19-21]. Three dimensional measurement dataset obtained by the equipped LiDAR on the six-wheel type robot was used to generate the map. A generated map is shown in Figure 5. As a result of this experiment, it was confirmed that the six-wheel type robot has sufficient running performance to construct a three-dimensional map under uneven terrain and inclined environment.

This robot was designed assuming to travel in a forest environment in order to generate such a 3D map. Therefore, it is desirable that the traveling system of the robot grips on the ground and travels stably, and does not cause excessive acceleration and vibration in the LiDAR. Thus, it is important to balance traveling performance and energy efficiency by adjusting the number of wheels.

Other experiments have been carried out with the robot moving in the external spaces of the Kyushu Institute of Technology; in the digital maps depicted in Figure **6** may be recognized features such as trees, flowerbed, columns and cart.

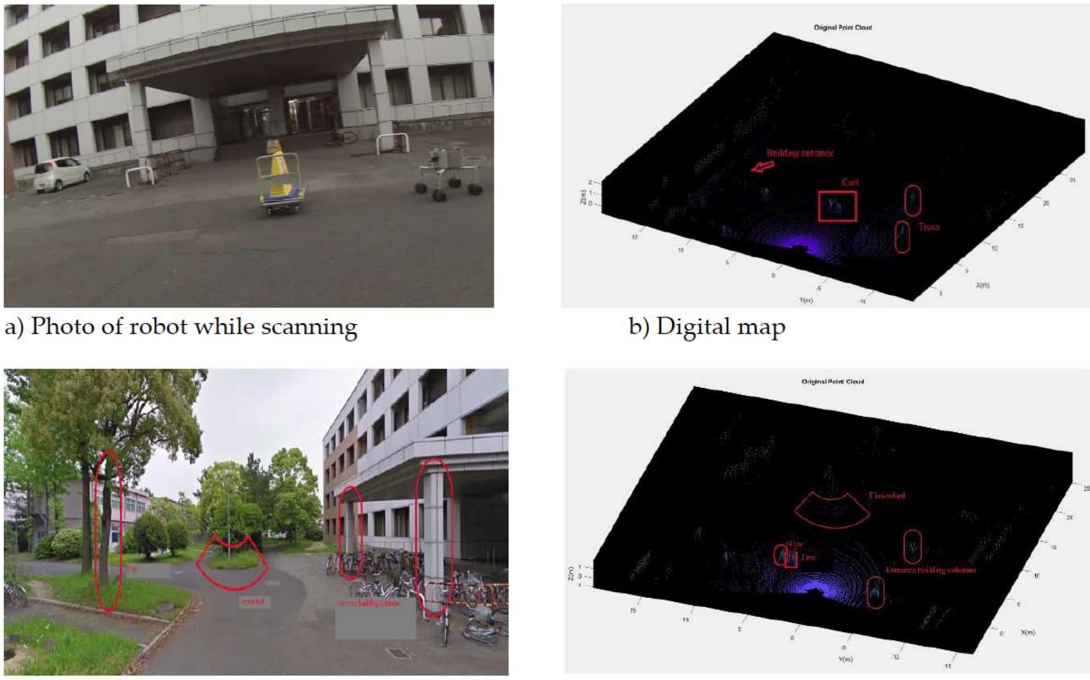
3.2. Relationship between the Number of Tires and Running Performance

The vibrations induced on the LiDAR sensor, placed on the top of the robot, during its movement could compromise the accuracy of the acquired cloud of



(a) Top view (b) Side view (c) Over view

Figure 5: Generated three-dimension digital map.



a) Photo of robot while scanning

b) Digital map

c) Photo from robot while scanning

d) Digital map

Figure 6: Generated three-dimension digital map.

points and also could ease the robot organs of unscrewing (as verified during the experiments). For this reason, a reduction of the vibrations choosing the best robot configuration (2,4 or 6 wheels) could become a strategic factor for the accuracy and the maintenance of the robot. At this proposal, an extensive experimental analysis has been carried out considering the data of the value of the vertical acceleration applied to the LiDAR by means of a Inertial Measurement Unit (IMU) placed inside the LiDAR box.

The tests have been conducted with a first phase of calibration, by considering a preliminary evaluation of the characteristics of the used accelerometer; in the preliminary tests the robot was still on the floor (see Figure 7) and the accelerometer acquired the vertical oscillations for a period of 30 seconds and sampling frequency 50 Hz. The standard deviations σ, expressed by Eq. (1), for 3 different tests are reported in Table 1, demonstrating the similarity of the standard deviation value and giving a confidence value of the vertical accelerometer accuracy.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(a(i) - \bar{a})}{N}} \qquad (1)$$

In (1), N is the total number of acceleration samples a(i) and $\bar{a}$ is the mean value, that is considered as accelerometer offset. The parameter introduced in (1) will be considered as the comparison parameter for the vertical oscillation for all the following experimental tests presented.

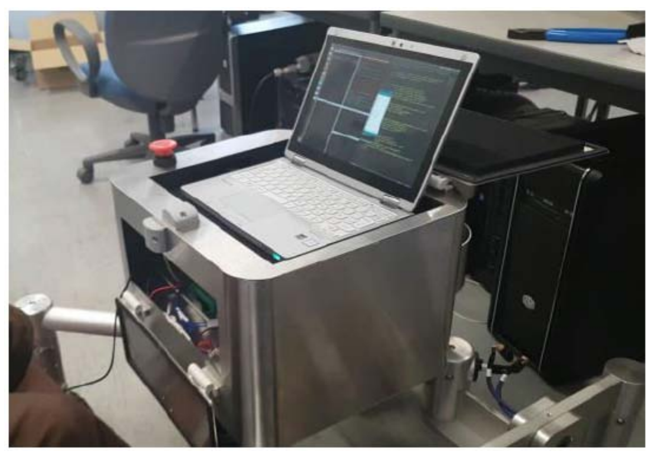


Figure 7: Preliminary calibration tests.

All the possible robot configuration, in relation with the possible surfaces scenarios have been measured when the robot was running at a constant speed. When the acceleration is small, it indicates that the plurality of wheels are appropriately grounded to the environment. If the acceleration is large, the wheels do not properly contact the ground, and a jump accompanying the rotation of the wheels occurs. That is, by comparing the acceleration in the vertical direction for each type of

Table 1: Standard Deviation of the Vertical Acceleration for 3 Tests with Still Robot

	First test	Second test	Third test
Vertical acceleration standard deviation σ	0.138	0.156	0.188

robot, it is possible to evaluate the running performance against the running environment. The values of a vertical acceleration sensor installed in the LiDAR at that time by running the three types of the robot with three types of environment of grassland and gravel road at a constant speed were measured. The three environment are shown in Figure **8**.

In each environments at least 3 experiments for each robot configuration (2,4 or 6 wheels) have been carried out in order to characterize the robot behavior and also to be guaranteed about the repeatability characteristics and a sampling frequency of 50 hz has been used. In Figure **9** an example of the results referred to the environment b) in Figure **8**, asphalt; it is evident a heavy difference of vertical acceleration for the 3 considered configurations. A more clear view may be carried out by Tables **2-4**, where for each type of environment, asphalt in Table **2**, grassland in Table **3**, Gravel in Table **4** the standard deviation of 3 different tests, named Test 1,Test 2 and Test 3, for each configuration (2,4 or 6 wheels) are reported. For the tests on gravel surface the configuration with 2 wheels was not able to move the robot, so only the results (2 tests) with others configurations have been reported.

Several considerations may be carried out analyzing the results in Tables 2-4 and considering

a) Gravel b) Asphalt c) Grassland

Figure 8: Three environments for experiments.

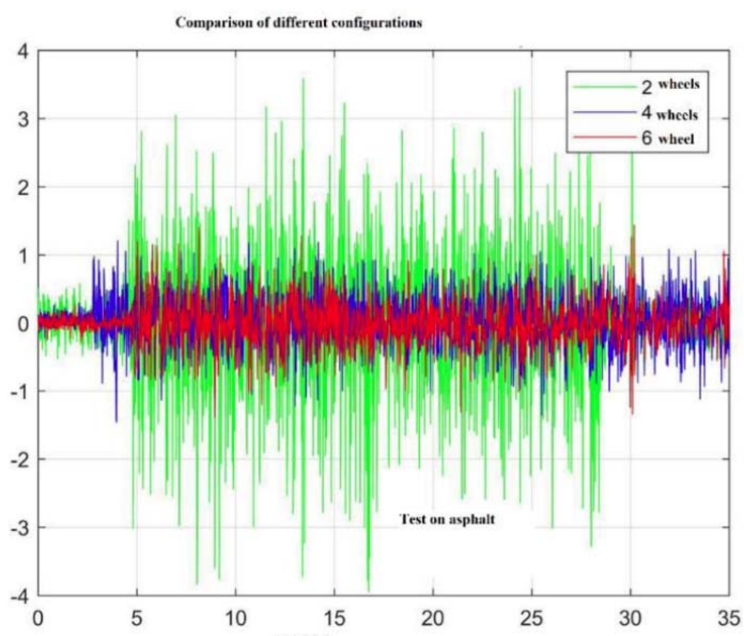


Figure 9: Vertical acceleration (in m/s^2) of Test 1 on the asphalt for 3 configurations. The value of gravity is excluded.

Table 2: Standard Deviation σ of the Vertical Accelaration

Environment: Asphalt	Two-wheel type	Four-wheel type	Six-wheel type
Test 1	0.99	0.42	0.37
Test 2	0.97	0.35	0.37
Test 3	1.1	0.37	0.39

Table 3: Standard Deviation σ of the Vertical Accelaration

Environment: Grassland	Two-wheel type	Four-wheel type	Six-wheel type
Test 1	0.95	0.42	0.37
Test 2	1.1	0.45	0.35
Test 3	0.93	0.41	0.37

Table 4: Standard Deviation σ of the Vertical Accelaration

Environment: Gravel	Two-wheel type	Four-wheel type	Six-wheel type
Test 1	-	0.53	0.48
Test 2	-	0.48	0.49

several other experiments that have been conducted also on mixed surfaces or hill-profile and so on:

- The parameter σ standard deviation gives effectively a precise trend for the different tests in the same configuration/surface and can assist in the choice of the optimized modular size with respect to the surface of movement;

- Globally, the configuration with 2 wheels, nevertheless the lowest weight, has the worst behavior with vibrations amplified of 2 times for every surface; even, the movement is not allowed with 2 wheels configuration on very irregular surfaces (like the gravel here considered);

- The configurations with 4 or 6 wheels, have similar behavior for all the tests, only a light preference may be given to the configuration with 6 wheels on soft surfaces (such as the grassland here considered), where probably the use of 2 more wheels may reduce the fluctuations and may improve the LiDAR scanning.

In order to conclude this analysis about the different configurations also an energetic evaluation of the new robot has been carried out evaluating, from the motor power, the total robot weight and plausible hypothesis of movement, the autonomy of the robot. It has been estimated an autonomy equal to 25 minutes for the configurations with 6 wheels, and 32 minutes for the 4 wheels robot with the actual battery of 3800mAh at 24 Volt. These estimated autonomy times have been confirmed by the experiments conducted.

4. CONCLUSION

In this paper a modularized driving wheels and a frame for connecting them in order to be able to adjust the balance between the mobile robot's runnability and energy efficiency according to the environment has been presented. The developed robot which can be constructed by combining the modules has a 3D LiDAR for generation of 3D digital map and travels through several environment with saving the energy by adaptively change the number and arrangement of the wheels according to the environment. Moreover, several experiments have been conducted for evaluating the performance and the characteristics of the developed robot. First, it was shown that the developed mobile robot can easily change the three types of mechanisms according to the environment by changing the number of modularized driving wheels and their combination. Next, it was shown by this mobile robot that it is possible to construct a 3D map by running on an outdoor rough environment. In addition, several experiments were carried out on three kinds of environments with three types of the robot, and the running performance was investigated by measuring the value of the acceleration sensor in the vertical direction. It was confirmed from the results that the the six-wheel type is suitable for an uneven and soft environment and the configuration with 4 wheels has similar characteristics and bigger autonomy for hard and rigid surfaces.

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