# Development of a Mobile Robot Platform for 3D Measurement of Forest Environments

Yuta ARITA, Enrico di Maria, Roberto Gallone, Luigi Capodieci, Masaru MORITA,
Kouta OKUBO, Nicola I. Giannoccaro, Mirei SHIGE-EDA and Takeshi NISHIDA

***Abstract*— Measurement of forest environments and trees is an important task in forestry. Because it is currently carried out manually, it is laborious. Thus, the development of an automatic measurement methodology deploying mobile robots would facilitate this labor and time consuming task. However, a severe forest floor environment comprising of rough terrains, bushes, and muddy ground poses a challenge for mobile robots. To overcome this challenge, we have developed a six-wheeled rover having a rocker-bogie suspension system and a 3D measurement sensor. First, the structure and electrical construction of the robot are explained. Next, the sensor system and software construction are described. Finally, we evaluate the 3D measurement and mapping ability of the developed robot through several experimental results in a real forest.**

## I. INTRODUCTION

In Japan, the number of people working in forestry is decreasing. The laborious nature of the work with very little automation has contributed to decrease. In such a situation, automation technology is an attractive proposition for the sustenance and management of forests. In this paper, we focus on the generation of digital three-dimensional (3D) maps in forests. Forestry maps are necessary to gather information about trees and generate felling plans. In recent years, engineers have been using laser gauges to carry out measurements by observing trees from multiple viewpoints. These 3D digital maps deliver greater detail than maps generated by UAV. Digital 3D maps are used to count the number of trees, to estimate their age, and to generate a navigation path for vehicles. While there have been studies which have provided systems that reduce operation time and deliver maps of higher quality [1], they were however not fully automated systems.

Hence, the purpose of our study is to create a fully automated system using mobile robots, which generates digital 3D maps of forests. For this, we first developed a mobile robot, which has a rocker-bogie suspension to move smoothly on rough terrains. A 3D LIDAR (light detection and ranging) sensor and a laptop were then mounted on the mobile robot to measure the distance of the robot to its environment. A driving system, which remains active while measuring the distance, was also integrated. Using this system, we carried out experimentations, in which digital 3D maps were generated by using the measured data gathered autonomously using the mobile robot and compared the accuracy of these 3D maps with maps created using manual measurements.

The experimentations revealed that digital 3D maps possess higher accuracy compared to maps from manual measurements. Furthermore, our system is also less time consuming.

## II. MOBILE ROBOT PLATFORM

Forest floors are undulating because of the roots and branches of the trees and forest vegetation. Additionally, dead vegetation and forest floor consistency serve as obstructions. For such environments, we need a robot, which has the mechanism to navigate smoothly. For this purpose, we developed a six-wheeled robot that adopted the rocker-bogie suspension mechanism shown in Figure. 1. In addition, we mounted a GPS antenna, a camera, an IMU, rotary encoders and a LIDAR on the robot in order to investigate optimal sensors for generating of 3D digital maps.

From several basic experiments, we could confirm that the GPS system did not function properly, as the signals interfered with the upper foliage of trees. Moreover, the measurements of the rotary encoders were disturbed frequently by a measurement error caused by the slip of the tires. The unevenness of the ground generates drift noise and causes vibration, resulting in an accumulation of measurement error in the IMU within a short period of time. Illumination was also an issue. During daytime, the illuminance difference between sun and shade is large and within the dynamic range of a normal camera, which makes it impossible to shoot them simultaneously. We therefore had to develop a method to create a digital 3D map using only the LIDAR sensor.

### A. *Rocker-bogie suspension system*

The rocker-bogie suspension system is a mechanism that enables a six-wheeled vehicle to keep all six wheels in contact with the ground passively and on an uneven terrain. The

TABLE I. SPECIFICATION OF YVT-X002

| Item | Specification |
|---|---|
| Horizontal scanning angle | 210° |
| Vertical scanning angle | 40 °(-5° ~ 35°) |
| Detection range | 0.3 ~ 25 m (white paper) |
| Number of data | 2590 points/frame |
| Sampling frequency | 20 Hz |

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Yuta A., Masaru M., Kouta O., Mirei S. and Takeshi N. are with Kyushu Institute of Technology, Kitakyushu, 804-0015, Japan(corresponding author to provide phone: 093-884-3190; e-mail: nishida@cntl.kyutech.ac.jp).

Enrico di M., Roberto G., Luigi C. and Nicola I. G. are with Salento University, Lecce, 73100, Italy. (e-mail: ivan.giannoccaro@unisalento.it).

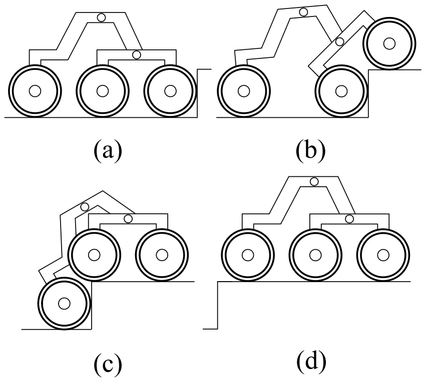
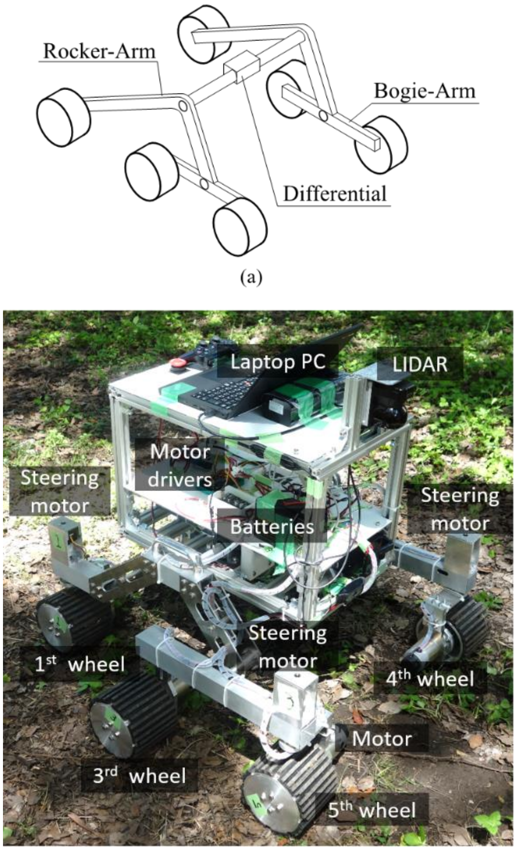


Figure 1. Sequence of overcoming an obstacle.



(b)

Figure 2. Overview of the developed robot. (a) Frame of adopted rocker-bogie suspension, and (b) overview. The left side is the frontside of the robot.

mechanism is shown in Figure 1. This mechanism allows to equilibrate the pressure of the wheels on the ground and avoid sinking while on soft terrain. Moreover, all six wheels keep contact with the ground when the robot encounters an obstacle. This helps it to negotiate obstacles. Further, the robot can negotiate obstacles larger than the wheels' diameter. This mechanism had also been adopted in the Mars exploration robot Curiosity [2]. This mechanism has a better performance than the crawler for overcoming steps. It causes almost no damage to the forest environment while traveling and the small contact area of the wheel results in a higher energy efficiency. Furthermore, it has a pivot turn function.

TABLE II. SPECIFICATION OF MOBILE ROBOT

| Item | Specification |
|---|---|
| Length | 0.95 m |
| Width | 0.96 m |
| Height | 0.90 m |
| Weight | 50 kg |
| Wheel motors | 40 W x6 |
| Steering motors | 7.6 N x4 |

The main components consist of a bogie arm, to which two wheels are attached and a rocker arm to which the third wheel is attached. The robot has the components on each side. A rocker arm and a bogie arm are connected by a revolute joint (bogie joint). A left rocker and a right rocker are connected by means of two shafts linked by a differential, similar to those used in automobiles. The setup is shown in Figure 2(a).

### B. *3D LIDAR*

We adopted 3D range sensor YVT-X002 (HOKUYO Automatic) as a LIDAR sensor. TABLE 1 lists the main specifications. We installed the sensor in front of the robot at a height of 0.86 m. The vertical scanning angle ranges between -5° and 35°, with the upper range being narrow. The sensor is installed upside down. The sensor can measure a distance of 25 m in sunlight and other disturbance light.

### C. *Other sensors*

The wheels of the rover have each a rotary encoder, which help it measure rotations of the wheels. The steering angles of servo motors too can be obtained. The inertial measurement unit (IMU) is installed in the center-bottom of the robot.

### D. *Hardware configuration*

We considered MDD10A (Cytron Technologies), which can control two motors for each, as the motor driver. We therefore installed three boards to control six wheel motors. For counting rotary encoder pulses, we connected iMCs01 boards (iXis Research) to the laptop using USB ports. To control the steering joint of the robot, the B3M-SC-1170 motor (Kondo Kagaku) was used. This was mounted on every steering joint.

Figure 2(b) shows the entire robot and TABLE II lists its dimensions and specifications.

### E. *Software configuration*

The robot operating system (ROS) [3] was adopted as the robot middleware. The ROS runs the program as a "node" independently. Nodes communicate with each other using TCP/IP protocol. Additionally, we developed a simulation

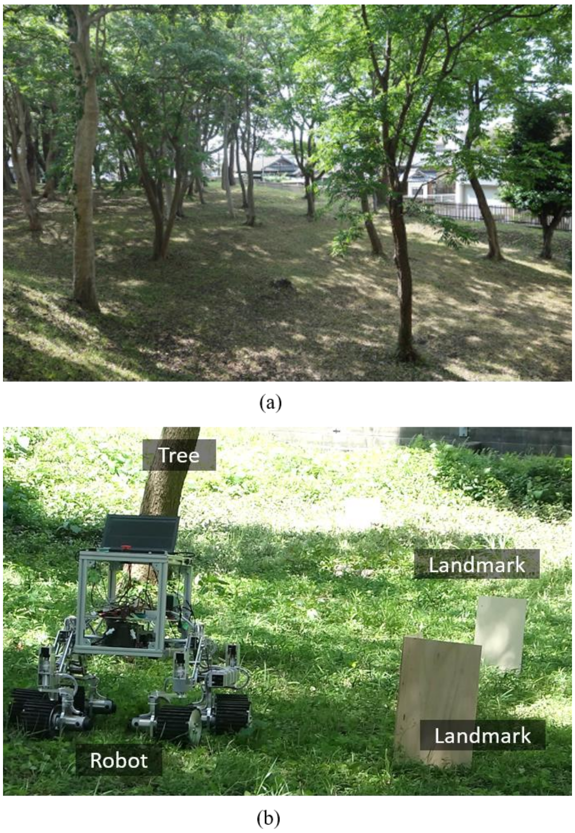

(a)
(b)

Figure 3. Experimental environment. (a) The target forest, there are many trees, and (b) the artificial landmarks had been installed in the environment in order to verify the accuracy of the generated 3D digital map.

environment using gazebo [4]. This allows us to test the robot controllers by running a simulation. As the robot is compatible with "ros_control," it can use controllers same as those used in simulations. Steering motors, which include controller boards, can be controlled directly by angle command using a USB-to-serial converter. The wheel motors are controlled by PID controllers

## III. POINT CLOUD PROCESSING

### A. *3D Mapping*

The motion estimation by odometry does not work well in a forest environment because wheels tend to slip. Because of this, in this study the motion estimation is executed by point cloud matching obtained by the 3D LIDAR. Some proposed methods for 6 degrees of freedom point cloud matching are, e.g., "Iterative Closest Point (ICP)" [5] and "Normal Distribution Transform (NDT)" [6]. ICP requires a long time to match a point cloud if the reference point cloud consists of a large number of reference points. On the other hand, NDT requires a constant time to match point clouds, regardless of the number of reference points in the reference point cloud. Therefore, NDT is adopted to estimate position and pose of the robot. We used NDT offered by the point cloud library (PCL). The digital 3D map is made by overlaying point clouds transformed by NDT. However, it takes a long time to make the map real-time. Hence, the point cloud is recorded framewise, and the map is then generated offline.

### B. *Ground plane removal*

The ground point cloud is removed from the digital 3D map to obtain the desired information. We used the RANSAC algorithm to estimate plane parameters. However, in the forest environment, it is difficult to estimate ground as one plane, because the ground is composed of different slopes. Therefore, in this study, the digital 3D map is divided into grids in the x-y plane; plane parameters are then estimated for each grid. However, if a grid includes point clouds of trees or other objects, the estimation can be incorrect. For example, the resulting plane estimation will be tilted with respect to the truth of ground plane because the trees' point clouds influence the estimation. For that reason, we evaluated the normal vector of an estimated plane to determine whether the result of estimation was correct. If it is true, the point cloud is removed. If it is false, the estimation is a failure and the point cloud is not removed. The threshold is defined by trial and error.

## IV. OUTDOOR EXPERIMENTATION

The time series point cloud data is obtained in the environment by a robot controlled remotely. As shown in Figure 3(a), the experimental environment has an easy slope and approximately 10 trees, which are approximately 0.3 m in diameter. Moreover, the ground is soft and there is humus present. This makes it easy for the wheels to slip. This makes the environment similar to that of a forest In order to compare the accuracy of our digital 3D map with a manual map, nine artificial markers are put on the field as shown in Figure 3(b)

## V. RESULT

The program is implemented in C++ and executed on a PC with an Intel Core i5-4440 processor running at 3.10 GHz x 4 and 16GB RAM.

### A. *Mapping accuracy*

Figure 4 shows the digital 3D map generated by the proposed system. The landmark positions are measured manually by four engineers as shown in Figure 5. To compare landmark positions, these need to be transformed from our digital 3D map's coordinate system to the manual map's coordinate system. In order to do this, ICP matching is used and a homogeneous transformation matrix is obtained. The matrix is then applied to our 3D map's landmark positions. The errors between our 3D map's and the manual map's landmark positions are shown in TABLE III. We see from TABLE III that the errors are at most 0.15 m. The sensor that is mounted on the robot has an error margin of ±100 mm at 25 m. The result of our experiment after considering the error margins, clearly shows that the digital 3D map provides a high accuracy. Moreover, in an actual forest environment trees are at least 1 m apart. Thus, the accuracy of our digital 3D map is enough to obtain information about trees and other objects.

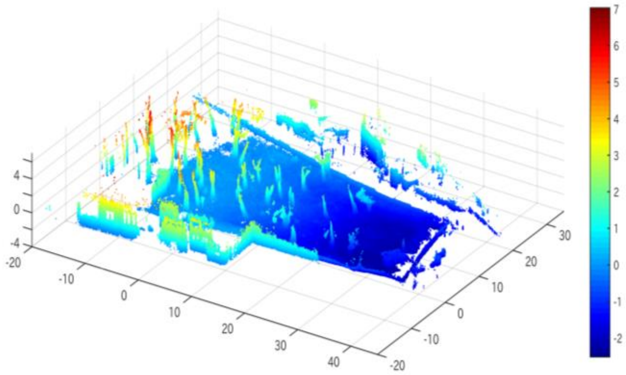


Figure 4. Overview of 3D digital map generated by our proposed system

TABLE III. THE ERRORS OF THE 3D DIGITAL MAP

| **Landmark** | **The errors** | | |
|---|---|---|---|
| | *X* **[m]** | *Y* **[m]** | *Z* **[m]** |
| 1 | 1.48E-01 | -3.06E-02 | -3.13E-02 |
| 2 | -1.12E-02 | 4.73E-02 | 2.76E-02 |
| 3 | -1.94E-02 | 5.55E-02 | -1.54E-03 |
| 4 | -1.19E-01 | -6.99E-02 | -6.38E-02 |
| 5 | -9.09E-02 | -3.30E-02 | -3.80E-03 |
| 6 | 2.78E-02 | 8.92E-02 | 1.19E-01 |
| 7 | -2.55E-02 | -8.39E-03 | 2.70E-02 |
| 8 | 2.93E-02 | -2.55E-02 | -5.92E-02 |
| 9 | 6.03E-02 | -2.45E-02 | -1.37E-02 |

### *B. Ground plane removal*

Figure 6 shows the result of the application of the method described in Section III B to the digital 3D map. We observe in the figure that removal of the ground plane is a success. The white rectangles represent the estimated planes.

## VI. CONCLUSION

As a result of this study, we constructed a mobile robot with ROS demonstrating a good traveling performance. Moreover, we developed a physical simulator to conduct robot development in a virtual environment. We executed experimentation of generating the digital 3D map in an environment similar to that in a forest. Validation of the digital 3D map revealed a maximum error amounting to 0.15 m compared to a manually created map. Besides, the digital 3D map requires just nine percent of the time required by four engineers to get the point clouds.

## VII. FUTURE WORK

In this paper, loop closing is not discussed. However, loop closing is necessary to improve the accuracy of the digital 3D map. While the robot is controlled remotely today, in our future work, it will navigate autonomously to take measurements needed to generate a digital 3D map.

Figure 5. Circumstances of taking manual map by engineers

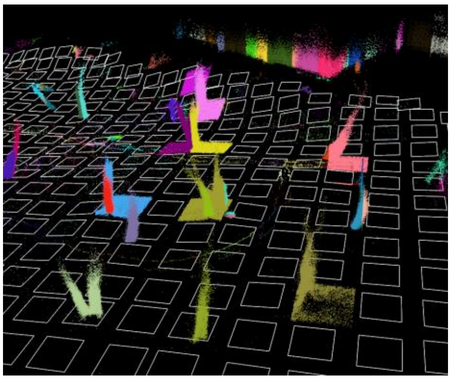


Figure 6. Extraction of tree’s point clouds and the ground recognition

Using the robot generated digital 3D maps, it was difficult to extract information regarding trees and terrain manually. In future, we will therefore try to automate this as well.

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