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Development of Safety Sensor for Vehicle-Type Forest Machine in Forest Road

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Abstract

A sensor system has been developed that uses an ultrasonic sensor to detect the downhill slope on the side of a forest road and prevents a vehicle-type forest machine from rolling down a mountainside. A specular reflection of ultrasonic wave might cause severe issues in measuring distances to targets. By investigating the installation angle of the sensor to minimize the negative effects of specular reflection, the installation angle of lateral monitoring ultrasonic sensor could be determined based on the width of road shoulder. Obstacles such as small rocks or piece of log in a forest road may cause the forest machine to be overturned while the machine riding over due to excessive its posture change. It was determined that the laser sensor could be a part of a sensor system capable of specifying the location and size of small obstacles. Not only this sensor system including ultrasonic and laser sensors can issue a warning of dangerous sections to drivers in forest forwarders currently in use, but also it can be used as a driving safety sensor in autonomous forest machine or remote-control forest machine in the future.

Key Words: forest machine, risk detection, ultrasonic sensor, laser sensor, distance sensor

Introduction

In Korea, not only has the logging season arrived from a forestry management perspective, but there is also an increasing demand for domestic timber (Kim and Shin 2022). To address the shortage of labor and enhance productivity, the mechanization of forestry operations has been urgently needed. To establish a stable domestic timber production system, the Korea Forest Service set up the plan to develop and distribute high-performance or large-scale forestry machinery suitable for forestry operations, along with securing forest roads for wood production (Korea Forest Service 2018). It is expected that the use of forwarding equipment will become more active.

Logging operations are inherently hazardous, with a high incidence of accidents. Even during the forwarding process, transporting logs from the work site to the collection point, there is a considerable risk of accidents such as rollovers, particularly on sloping and unpaved roads. For example, in December 2021, in a forested area in Jeonnam province, South Korea, a forwarder operator died when the transport route collapsed after rainfall in a hairpin turn section. Similarly, in January 2019, in a forested area in Gangwon province, a logging operator died when a forwarder rolled off a slope with excessive slope during timber transportation (Korea Occupational Safety and Health Agency 2022). These incidents were attributed to insufficient road environment awareness and inadequate op-

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eration of vehicle control equipment in hazardous sections such as hairpin turns. In addition, obstacles such as tree debris or rocks on the logging road may go unnoticed by the operator of tall forest machine. If one of the wheels of the forest machine rides over such obstacles, it may be exposed to excessive slopes, increasing the risk of overturning.

Typically, logging roads have a width of about 3 m with approximately 0.5 m of shoulders on both sides (Ordinance of the Ministry of Agriculture and Forestry 2006). One side is inclined, and the other side is a steep slope, demanding careful driving to avoid getting too close to the steep slope. When obstacles fall on the road or when certain sections have subsided, more attention is required to navigate. Therefore, this study attempts to build a safety sensor system for forwarders using various sensors that can perceive such driving environments.

Ultrasonic, laser, and radar sensors operate as time-of-flight (TOF) sensor, measuring the time it takes for the medium used by the sensor to be transmitted from the sensor to a target and reflected until it reaches the sensor. They then apply the speed of propagation of the medium to measure the distance. These sensors exhibit specular reflection characteristics, meaning that the reflection characteristics vary depending on the incident angle of transmitted signal and the roughness of the target surface (Lim and Kim 2019). Kim (2001) reported that for ultrasonic sensors in wall recognition devices for mobile robots, the measurable threshold angle for distance measurement varies depending on the surface roughness, such as 22.5° for wooden walls and 70° for brick walls. Madola (2022) experimentally confirmed that the absolute intensity of reflected signals decreases as the incident angle of ultrasound increases, stating that the threshold incident angle is about 30°. Ha and Kim (2006) demonstrated that ultrasonic sensors, due to their substantial beam angle and conical projection, measure distance by receiving signals reflected from a large area of the target. Thus, there can be distance measurement errors depending on the orientation, i.e., the installation angle of the sensor, as the sensor measures the signal from the nearest part of the target.

Logging roads are often mixed with grass and debris on crushed rock pavement or soil, making it more likely for ultrasonic sensors to receive reflected waves even when the incident angle is large. Even in cases of downhill slopes, distance measurements to the target can be possible. Therefore, this study explores the application of ultrasonic sensors to detect steep slopes from road surfaces with a rough terrain. Laser sensors, while having limitations in recognizing targets when exposed directly to sunlight outdoors, can measure the distance and localize its position for very small specific obstacle by transmitting and receiving the medium in a pinpoint manner. Additionally, this study aims to develop a detection system that can judge the height and position of small obstacles in the forward path of forest machine.

Materials and Methods

Principles of detecting the starting point of downhill slope (dangerous region)

An ultrasonic sensor transmits ultrasonic waves with a given beam width, receives a signal that is reflected from the target, and measures the distance to the target using the time difference between transmission and reception. Since the ultrasonic wave reflected from the closest point within the beam width is received first, the distance to target is determined by the distance from the sensor to the nearest point within the beam angle. As shown in Fig. 1, when ultrasonic waves are transmitted in an inclined direction to the horizontal plane, the distance to point D_1 is regarded as the measured distance. When the ultrasonic sensor is installed tilted at the height H and the installation angle θ, and the beam angle is ϕ, the ultrasonic beam projected on the horizontal plane covers the elliptical region between points D_1 and D_2, and the distance is determined by the distance to nearest point on the plane. Therefore, the distance to target

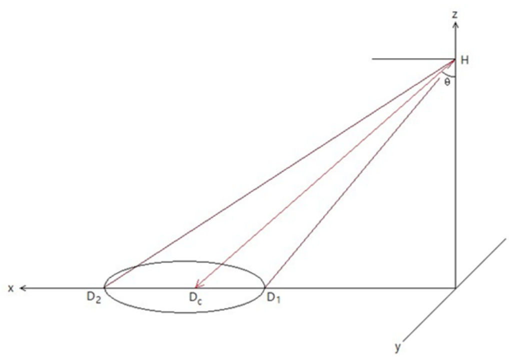

Fig. 1. Theoretical detected area by tilted an ultrasonic sensor.

surface can be calculated as in Eq. (1).

$$d = \frac{H}{\cos(\theta - \frac{\phi}{2})} \quad (1)$$

And the distances to point D_1 and point D_2 are as in Eq. (2).

$$x_{D_1} = H\tan(\theta - \frac{\phi}{2}) \quad (2)$$

$$x_{D_2} = H\tan(\theta + \frac{\phi}{2})$$

To avoid direct reflection from the vehicle body, the ultrasonic sensor must be installed at an installation angle of at least 11°. The section from the vehicle to point D_1 becomes a blind spot. The ultrasonic sensor starts detecting the downhill slope if the vehicle moves toward downhill slope by (D_2-D_1).

Construction of a driving safety sensor system

Ultrasonic sensor

Ultrasonic sensors have the characteristic that as the operating frequency increases, the beam width decreases and the accuracy of distance measurement improves accordingly.

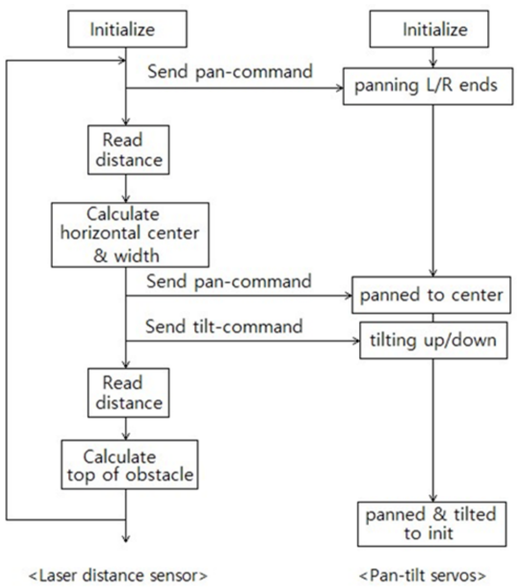

Fig. 2. Obstacle direction/height detection algorithm.

The ultrasonic sensor (URM15, DFROBOT, Chengdu, China) used in this study operates at a frequency of 75 kHz, has a beam angle of 20±2°, and offers a distance measurement resolution of up to 1 cm. The measurement frequency can be up to 10 Hz, and the distance can be measured with an accuracy of 1% within the range of 3 to 500 cm. The measured distance data output through RS-485 communication.

Laser sensor and pan/tilt servo

The laser sensor (MB2D, JRT Meter Tech, Chengdu, China) uses a green laser with an output of 1 mW and can measure at a cycle of up to 20 Hz with a resolution of 1 mm. The measured distance data output through RS-485 communication. Pan/tilt device consisting of two servomotors (Herkulex DRS-0201, Hyulim Robot, Cheonan, Korea) is used to control the posture of the laser sensor in terms of pan and tilt angles. By measuring the distance to small obstacle including pan and tilt angles at the time of distance measurement, the location of obstacle by its direction and distance and its height can be obtained.

If it is checked by an ultrasonic sensor that there may be an obstacle in the path ahead of the forest machine, the laser sensor proceeds scanning over the region at a tilt angle where small obstacle may be detected. After calculating the center line of the obstacle to fix the pan angle, the laser sensor proceeds scanning from up to bottom and finds a top of obstacle (Fig. 2).

As shown in Fig. 3, the distance to target surface measured by the laser sensor keeps decreasing as the tilt angle decreases on the flat surface. The measured distance decreases abruptly when it detects the obstacle. This point can be considered as the top of obstacle. Thus, the height h_o can be calculated as in Eq. (3).

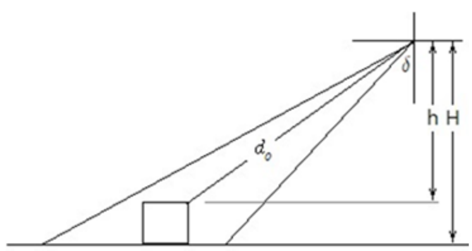

Fig. 3. Height of obstacle.

$$h_o = H - d_o \cos \delta \quad (3)$$

where, d_o: measured distance, δ: tilt angle.

AHRS sensor

AHRS (Attitude and Heading Reference System) sensor (MW-AHRSv1, NTRexLAB, Incheon, Korea) was placed at the center of upper plate in the experimental bogie to measure the posture of vehicle in terms of roll and pitch angles. Roll, pitch and yaw angles are measured at a rate of 1 kHz and output through RS-232, which converted into RS-485 communication.

DAQ system

For the instrumentation and control sensors and actuators are operated by Arduino Mega2560R3 Compatible board. Final data from sensors are transferred to main MCU with SD card installed through RS-485 communication.

Experimental bogie for DAQ system

The experimental bogie is 600×400×800 mm in size and has hub wheel motors (ZLLG80ASM250-4096 V2.02, ZLTECH, Shenzhen, China) mounted on the left and right sides of the front axle while the same size of caster wheels (S-530, KangnamCasterNet, Seoul, Korea) mounted on the real axle, and powered by DC 24V battery. A 2-channel motor driver (ZLAC8015D, ZLTECH, Shenzhen, China) is used to control the speed of hub motor and steering is also possible by the difference of both front wheel speeds. In the rear wheel-type rotary encoder (ENC-1-1-T-5, Autonics, Busan, Korea) was installed by conducting 5th wheel function, which measures the travelled distance of the bogie without slippage (Fig. 4).

Experimental methods

Reflection characteristics of ultrasonic sensor

To investigate the reflection characteristics of ultrasonic waves, the transmission direction of the ultrasonic sensor was set as, and the distance to the reflective surface was measured at the sensor installation angles from 0° (vertically downhill) up to 50° by increasing 15°. In addition, since the reflection characteristics are affected considerably by the roughness of surface, all experiments were carried out on various surfaces such as bare soil, crushed stone paved area and grass field. Measurements were taken for 1 minute and data were analyzed to investigate their reflection characteristics.

Downhill slope detection

Artificial downhill slopes were created indoor by pacing one end of a plywood board on a 4 m long table and the other on the floor. By moving the experimental bogie on the table toward the downhill slope, the distances to ground surface were measured in different downhill slope angles such as 30°, 60° and 90°. The ultrasonic sensor was fixed at the installation angle of 30°.

Detection of small obstacle in front

A carton box of 130×80×90 (W×D×H) mm in size was placed in front of the laser sensor. Distance measurements were made while panning from -30° (right)-+30° (left) by increasing 2° and tilting from 70° (up)-40° (down) by decreasing 2°. Locations of obstacle were -15°, 0°, 15° along the path of panning 1,300 mm apart from the sensor for the panning test while 1,130 mm, 1,400 mm, 1,800 mm along the path of tilting for the tilting test. The experiment was conducted indoors with the bogie stationary.

Results and Discussion

Distance measurement performance on sensor installation angle and surface roughness

The ultrasonic sensor is lifted forward at an angle of 11°,

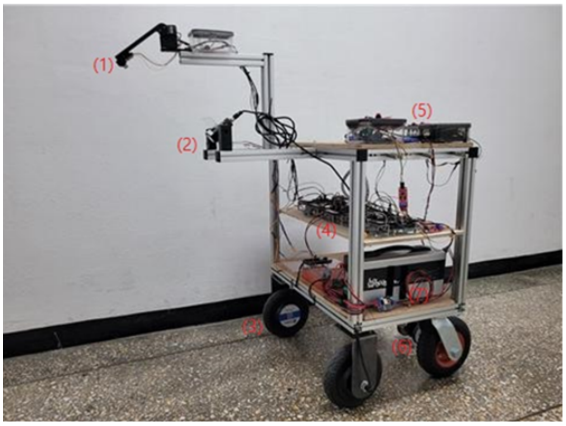

Fig. 4. Experimental bogie for measurement: (1) laser sensor, (2) ultrasonic sensor, (3) in-wheel motor, (4) sensor controllers, (5) vehicle driving controller, (6) 5th wheel sensor (in rear, not shown), (7) power supply (battery).

which is equivalent to 1/2 of the ultrasonic beam width, with respect to the vertical direction, and this was subsequently considered to be the installation angle of 0°. It is true that the possibility of specular reflection increases as the sensor installation angle increases, however, there is not much difficulty in measuring the distance to the reflective surface due to diffusive reflection from the surface with large roughness.

Fig. 5 shows the results of the distance measurement experiment depending on the type of ground surface and sensor installation angle. On bare soil surface the ultrasonic sensor worked stably at the sensor installation angle of up to 30°, but fluctuations of over 100 mm were observed at the higher sensor installation angles, which was believed to be caused by specular reflection. Likewise, on crushed stone paved area the distance to ground surface was measured stably up to the sensor installation angle of 30°. Over the sensor installation angle of 45° there was fluctuations in the distance data. Compared with bare soil surface its amplitude of fluctuation was observed smaller. Crushed stones seemed to play important role to reflect the ultrasonic wave diffusively. On the ground surface where a lot of grass has grown, the fluctuations were more severe than 200 mm at the sensor installation angle of around 30°, but as they increased up to 45° and 50°, the fluctuation range tended to be similar to that on the bare soil surface. In addition, as shown in Fig. 5, the average distances were measured shorter than the theoretical values at the smaller installation angle. This seemed to be because not only the directions of the standing grass leaves were various, but also tall grass leaves caused the reflections occur inconsistently.

For purpose of use, the presence or absence of reflected ultrasonic waves is more important than accurate distance measurement. As far as the measured distance is concerned, the average of fluctuating distance data is enough. It is believed that if the sensor installation angle is maintained within 30°, the distance can be measured stably by receiving reflected waves from a reflective surface.

Detecting performance of downhill slope

While a vehicle-type forest machine is driving on a forest road, the presence of a downhill slope on the side of the vehicle has a decisive influence on the safe operation of the forest machine. While driving, the road shoulder area on the side should be continuously monitored, and if a slope is detected, steering control should be immediately implemented to prevent the vehicle from approaching the downhill slope. Figs. 6-8 are the results of measuring the distance of the ultrasonic sensor while driving the experimental bogie toward downhill slope in an indoor environment where slopes of 30°, 60°, and 90° were artificially installed.

As shown in Fig. 6, it was found that it was possible to receive ultrasonic waves reflected from the target reflection surface to some extent up to a downhill inclination of 30°. As the sensor installation angle increases, the farther away the area is seen, the faster the slope is detected. In other words, it was judged that it was possible to detect the starting boundary of downhill slope in advance and thereby secure a safe area.

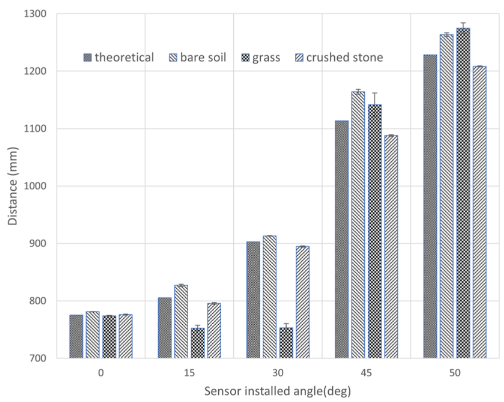

Fig. 5. Reflection characteristics of ultrasonic sensor on sensor installed angle and type of surface.

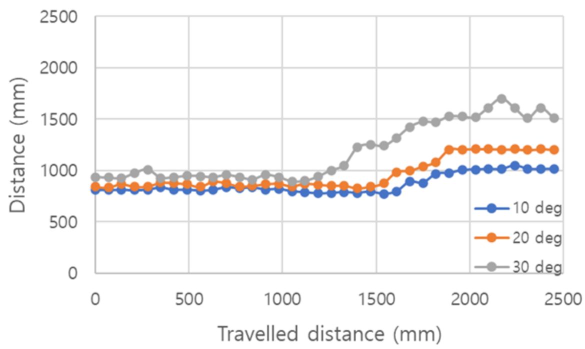

Fig. 6. Distance to target surface at the downhill slope of 30°.

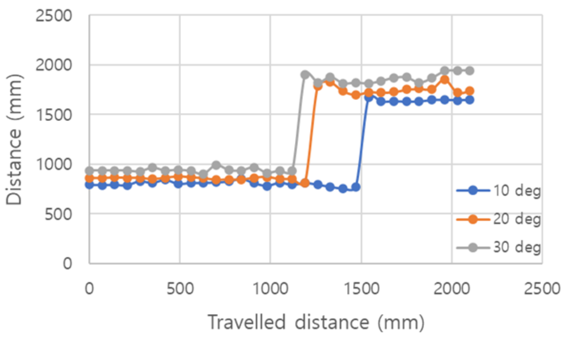

Fig. 7. Distance to target surface at the downhill slope of 60°.

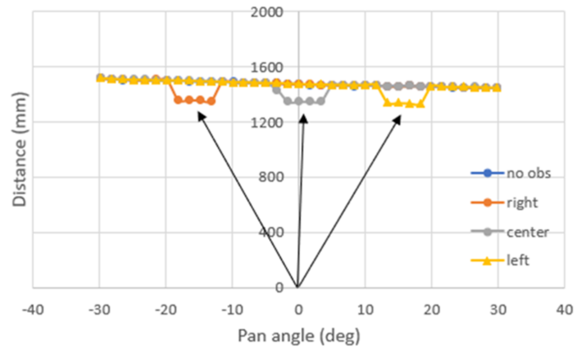

Fig. 9. Direction detection of obstacles while panning.

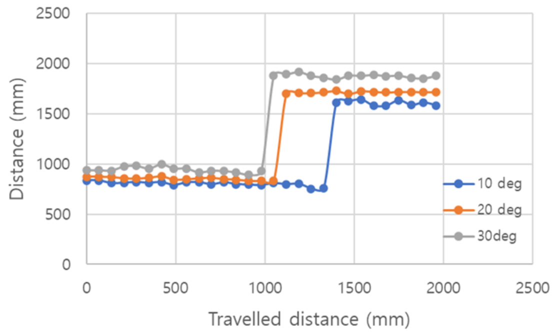

Fig. 8. Distance to target surface at the downhill slope of 90°.

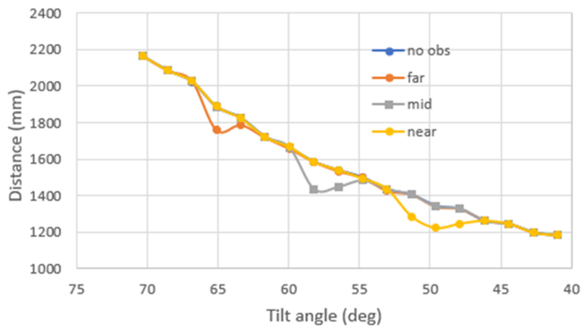

Fig. 10. Height detection of obstacles while tilting.

As shown in Fig. 7, when the downhill slope reached 60°, it was observed that no ultrasonic waves were reflected from the slope itself, and rather the bottom surface (floor) after the slope boundary was detected. When the sensor installation angle was large, the inclined boundary surface was detected earlier. In the case of very steep cliff with a downhill slope of 90° in Fig. 8, there was no significant difference from the 60-degree slope, except that the change of measured distances in the boundary surface was more rapid.

Therefore, it was concluded that once the area to be monitored in the given road shoulder was determined, the sensor installation angle could be determined accordingly.

Location and size detection performance of small obstacle

Fig. 9 is the result of panning the area where small obstacle existed from right to left and measuring the distance with a laser sensor. If there was no obstacle, the distance to the reflection surface determined by the tilt angle of laser sensor would be measured without value change to be appeared as a horizontal line parallel to the horizontal axis. Nevertheless, the reason why the horizontal line was slightly tilted to the right is because it was measured when the experimental bogie was tilted to the left at a roll angle of approximately 2°. Since the distance was measured abruptly shorter on an obstacle on the panning path, so its presence could be easily detected. By applying the algorithm shown in Fig. 2, the center position of the obstacle could be obtained. Obstacles were measured approximately to be located at 0° and 15° on the left and right sides, respectively.

Once the center position of the obstacle was determined to fix the pan angle, and the distances to the obstacle were measured while tilting the laser sensor from up to the bottom. Since the angle of the tilting servo could be known in real time, the theoretical distance when there were no obstacles could always be known, and if the actual measured distance suddenly became smaller than the distance calculated theoretically, it could be judged that the top of the obstacle has been detected. As a result of calculating the height of the obstacle by applying Eq. (3), the height of obstacles located far, middle, and near distant from the sensor were measured to be 68 mm, 93 mm, and 83 mm, respectively, showing an error of about 3 to 24% (Fig. 10).

Conclusion

A sensor system was developed to detect the downhill slope on the side of a forest road and to prevent a forest machine from rolling down a mountainside. It could also detect small obstacle that forest machine might ride over and, as a result, prevent possible overturns.

By investigating the sensor installation angles that serve as criteria for measurement defects due to specular reflection, the installation angle of the side-view monitoring ultrasonic sensor could be determined based on the width of the forest road shoulder. Laser sensors was deemed suitable for use in a sensor system that can identify the location and size of small obstacles.

Considering dynamic characteristics, the development of a system that can optimize response time is deemed necessary for future research. It is anticipated that the development of an affordable system capable of replacing expensive LiDAR systems would be possible.

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