한국압력기기공학회 논문집
제16권 제1호 2020년 6월 pp. 84-91

ISSN 1738-8333
http://dx.doi.org/10.20466/KPVP.2020.16.1.084

<연구논문>

A Mobile Robot Based on Slip Compensating Algorithm for Cleaning of Stud Holes at Reactor Vessel in NPP

Dong Il Kim† and Young Jun Moon*

(Received 15 May 2020, Revised 12 June 2020, Accepted 17 June 2020)

ABSTRACT

The APR1400 reactor stud holes can be stuck due to high temperatures, high pressure, prolonged engagement, and load changes according to pressure changes in the reactor. Threaded surfaces of a stud hole should be cleaned for the sealing of pressure in reactor vessel by removing any foreign materials which may exist in the stud holes. Human workers can access to the stud hole for the cleaning of stud holes manually, but the radiation exposure of human workers is increased. Robot is an effective way to work in hazardous area. So we introduced robot for the cleaning of stud holes. Localization of mobile robots is generally based on odometry, but with increased mileage, position errors can be accumulated. In order to eliminate cumulative error and to ensure stability of its driving, laser sensors and new control algorithm were utilized. The distance between the robot and the wall was measured by laser sensors, and the control algorithm was implemented so as to travel the desired trajectory by using the measured values from sensors. The performance of driving and hole sensing were verified through field application, and mobile robot was confirmed to be applicable to the APR 1400 NPP.

Key Words : Reactor stud hole, Threaded surface, Mobile robot, Odometry, Slip compensating algorithm

Nomenclature

r = radius of wheel
ω = theoretical angular velocity of robot
ω' = absolute angular velocitiy of robot
v_r = theoretical velocity of the right wheel
v_l = theoretical velocity of the left wheel
v = theoretical linear velocity of robot
v' = absolute linear velocity of robot
a_r = slip ratio of the right wheel
a_l = slip ratio of the left wheel
$2d$ = distance between the wheels.

† Department of Mechanical Engineering, Chonnam National University
E-mail : pontoon@naver.com
TEL: (061)345-0562 FAX: (061)345-0309
* KEPCO KPS

1. Introduction

Nuclear power plant is a major power generation facility in Korea. A nuclear power plant is a thermal power station in which the heat source is a nuclear fuel in the reactor vessel. As it is typical of power stations, heat is used to make steam that drives a turbine connected to a generator that produces electricity.

The APR1400 reactor (Fig.1) consists of the reactor pressure vessel and the reactor head, those are tightened with stud bolts into holes for pressure maintenance.

The APR1400 reactor may be driven for a long time under high temperature conditions, causing thread damage in stud holes, resulting in stud bolts and holes sticking.

To prevent this adverse effect, anti-seize agent is applied to studs and holes every cycle before plant operation. Anti-seize agent is usually required to remove completely

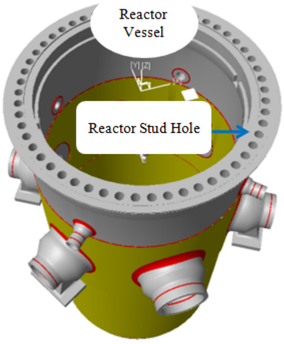

Fig. 1 Reactor Vessel

during the outage. The anti-seize agent is removed by workers from the vicinity of the reactor vessel, which is a high radiation zone. The radiation exposure is increased by manually cleaning stud holes in the high-radiation zone. In the event of fuel damage, the radiation dose rate increases significantly. To reduce the radiation exposure and the repair time of the worker, a mobile robot is useful to clean automatically the reactor stud holes. Mobile robot for nuclear maintenance may be appropriated to use in many areas and a remote operation seems to play an important role in reducing radiation exposure.

Stud holes are visually inspected the surface conditions of the thread. If damages occur, it should be remedied. If foreign materials remain, it must be removed. Damage to the threads (Fig.2) may increase the maintenance time and cost, which can have a significant impact on power supply and safety.

To clean the reactor stud holes, Mobile robot should be drive along the path and stop in the correction position. Accurate driving of robot is important because misalignment of robot relative to the stud holes cannot perform cleaning task. Odometry data using wheel's encoder sensor plays an important role in estimating the location of mobile robots. Odometry, one of the localization methods, is based on the assumption that wheel revolutions can be translated into linear displacement relative to the floor. However, if one wheel was to slip on, then the associated encoder would register wheel revolutions even though these revolutions would not correspond to a linear displacement of the wheel. So, the disadvantage of odometry is its unbounded accumulation of errors due to wheel slippage.[1-3]

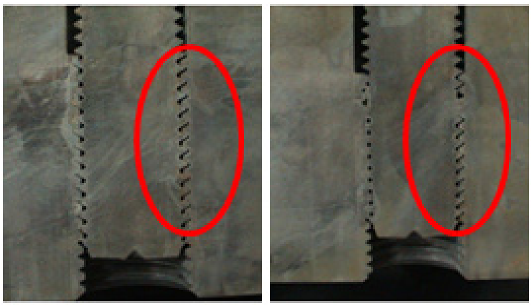

Fig. 2 Normal (left), Sticking (right)

Various methods for correcting odometry error have been studied. One of the methods was to design a controller that is able to compensate for the slip without estimating or measuring it[4]. And other method was that wheel slippage is estimated from motor current measurements, and encoder readings are adjusted[5]. Sutoh et al. proposed a mathematical model that expresses a relationship between the input and output velocities of the mobile robot from the test dataset[6]. A method for combining an inertial navigation system (INS) with the wheel encoders was presented[7]. A mobile robot localization was estimated the slip ratios using encoders (attached to the actuators) and a gyro-sensor[8]. Two PSD sensors are used to suggest a way to control wall following [9]. Three ultrasonic sensors were installed and wall tracking was implemented using the proposed algorithm [10]. However, due to the problem of crosstalk of ultrasonic sensors, the reliability of the distance data could not be trusted in sudden geometrical changes[11,12]. The method of determining the position using internal sensors such as encoders and gyroscopes has its disadvantage that the error is accumulated in proportion to the traveling time and the distance. The external sensor like laser sensors is desirable to detect obstacle, to measure the distance and also to measure the orientation from the mobile robot to the wall to overcome shortcomings of internal sensors[13].

A new method for correcting errors of robot position in the reactor stud hole was presented using an laser sensors and encoders for true path tracking. The adequate control algorithm was also presented. The paper is organized as follows. Section II explains the mobile robot platform, the mechanism, the sensors, and the control. Section III derives the kinematic model and proposes the wall following algorithm. Section IV depicts performance results. Section V shows conclusions.

2. Robot Platform

2.1 Mobile Robot

The system consists of robot, control system, and an auxiliary facility.(Fig. 3)

The mobile robot moves on the reactor vessel flange with four wheels to clean the stud holes. The mobile robot is driven in a circular direction and has two gripper to fix when cleaning (Fig.4). The mobile robot operates the gripper when it is arrived in a hole to be clean and is ready to clean. So, central rotation axis can be inserted into the hole, and then the entire threads are brushed.

If the robot is located in the hole to be cleaned, it spread the gripper with the air cylinder and lower it in the downward direction to hold the stud hole(red arrow Fig.4). To minimize the adverse effects of the grip surface, the grippers have a cylindrical rollers. When the grippers are closed, Robot is moved backward/forward for a second. It adjusts the position of the mobile robot for centering.

After grip is completed, the brushing module is lowered. Then the brushing module is used for cleaning. The individual wire brushes place at an angle of 90 degrees (Fig.5).

Typical brush form is made larger than the stud hole to clean the stud hole threads. Due to the radius of wire brush greater than the radius of the stud hole, there is a great rotational resistance caused by friction between the brush and the stud hole.

To solve this problem, the brushes are made in a circular shape and installed vertically to rotate freely. Therefore, the insertion resistance is minimized when the brushes are inserted into hole. The brushes are extended individually by centrifugal force at the time of rotation, and the thread cleaning is carried out (Fig.6).

When the brushing module rotates and falls, the centrifugal force causes the wire brush to come into contact with the threads. The contacted wire brush removes debris from the threaded flank and root. The brushing module is lowered to bottom of the stud hole and raised again. By performing several downward and upward actions, foreign materials are completely removed (Fig.7).

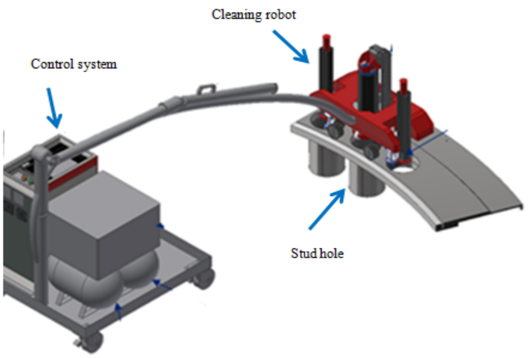

Fig. 3 Overview

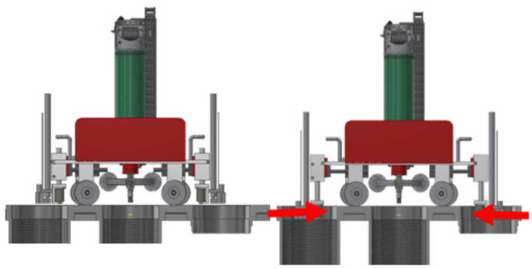

Fig. 4 Gripping

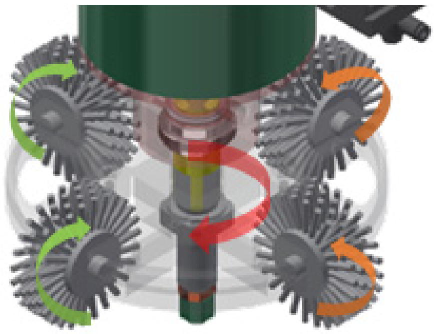

Fig. 5 The brushing module

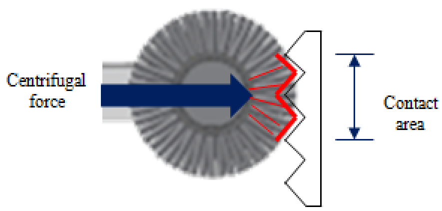

Fig. 6 Centrifugal force

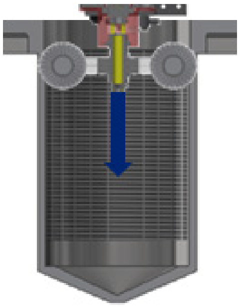

Fig. 7 Brushing Module

There are two internal flow paths. One of the internal flow paths allow the cleaning agent to be sprayed directly in the direction of the thread. So the foreign materials could be removed on the threaded surface.

The other is for suction of foreign materials from threads. When the brushing module touches the bottom of the hole, the internal flow path for suction is opened to inhale the foreign materials on the bottom of the hole.

2.2 Control System

The control system consists of a local control unit and a robot drive unit. For the user interface, the main configuration consists of a main screen, an IO and history screen (Fig.8).

When it is in auto mode, the robot is allowed to drive in the circumferential direction without operator, and sensors which is mounted on the mobile robot make it possible to detect obstacles. The robot cleans the holes while driving 360 degrees around the reactor.

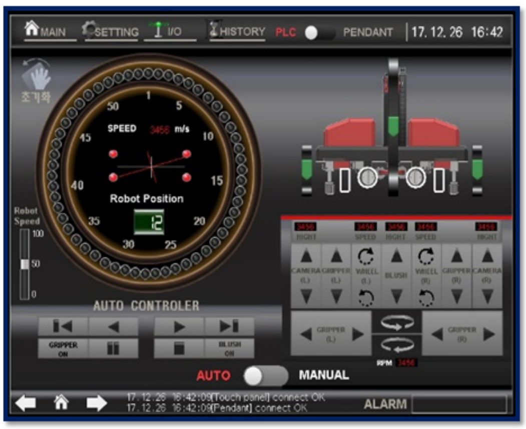

Fig. 8 GUI

In the case of manual mode, operator operates the robot directly and the operating conditions can be changed on the setting screen. The main functions, such as gripping, brushing, injection, and suction, are made possible respectively.

3. Localization

3.1 Driving

The desired trajectory shown in Fig 9 is the red line, and the robot is driven along the path by controlling the speed of the motors according to the direction of the mobile robot's driving.

Localization is one of the basic and difficult problem of mobile robot. The position and direction of the robot should be obtained so that the robot can move to its destination. There are various technologies for localization, but there are odometry technology that

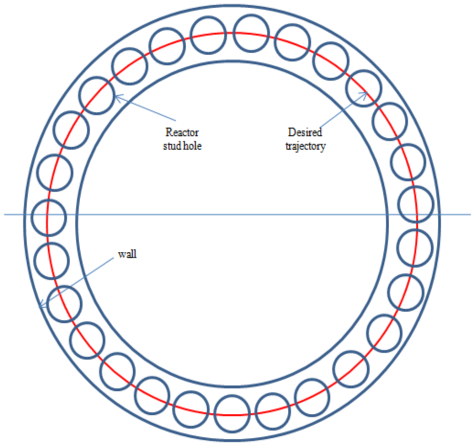

Fig. 9 Robot path(red line)

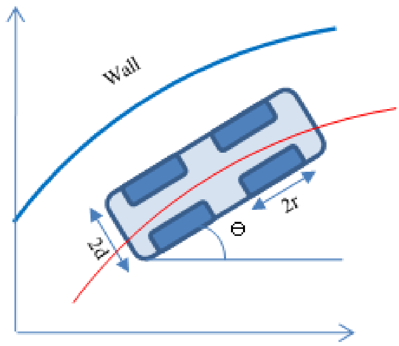

Fig. 10 Kinematic

measures wheel rotation. Odometry is an easy way to predict its location and direction, but it is assumed that there is no slip with the ground. Kinematic, assuming no slip, is the following equations (1-4). This formula is only satisfied when the mobile robot is pure rolling and non-slipping.

$$v_r = r\omega_r \tag{1}$$

$$v_l = r\omega_l \tag{2}$$

$$v = \frac{v_l + v_r}{2} \tag{3}$$

$$\omega = \frac{v_l - v_r}{2d} \tag{4}$$

However, it is difficult to apply those equations to estimate its true location and direction because of its slip. Thus, the traditional odometry method cannot be trusted that the mobile robot follows a given path. The modified kinematic, which reflects the effect of actual slip, is the following equations (5-6).

$$v' = \frac{v_l(1-a_l) + v_r(1-a_r)}{2} \tag{5}$$

$$\omega' = \frac{v_l(1-a_l) - v_r(1-a_r)}{2d} \tag{6}$$

If the slip ratio of the right/left wheel was zero, Equation (5-6) are the same as the theoretical equation (3,4) that does not consider slip ($v = v'$, $\omega = \omega'$).

However, not only is the slip ratio impossible to calculate accurately, but the slip ratio cannot be made zero. So it is important to find a way to bring the slip ratio as close to zero as possible. There have been various studies that measure or assume this ratio. In order to correct error from slip, we used an external sensor because it is incorrect with an internal sensor. The laser sensor was mounted on the side of the robot to measure the distance to the wall. By measuring the distance to the wall, the robot was allowed to move within a specific range. Even if the slip occurs while driving, the position was corrected by changing the speed of the left and right motors. Therefore, the distance between the robot and the wall was measured by laser sensors, and the control algorithm is implemented so as to travel the desired trajectory.

An ideal path for the robot is to drive around the reactor while maintaining a constant distance from the wall as shown in Figure 11. However, The actual trajectories of robot do not line up to the target path due to increase of the robot's slip with the wheels and the reactor surface.

A mild slip of the mobile robot results in a situation where Y1 or Y2 is out of range (Figure 12). As shown in Figure 12, the robot's posture is changed due to an increase in Y1 and a decrease in Y2. If it continues, the robot will deviate from the desired path.

Y1, Y2 are within a defined range in case of normal driving on the path, but if the value of Y1 or Y2 is out of range, the robot is out of the path. It is determining the degree of deviation according to the values obtained through each laser sensor.

The control algorithm was used to calibrate the robot's posture when it is out of the range.

$$\text{constant } 1 \le Y1 \le \text{constant } 2 \tag{7}$$

$$\text{constant } 1 \le Y2 \le \text{constant } 2 \tag{8}$$

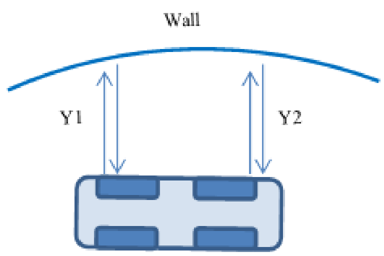

Fig. 11 Ideal posture of robot

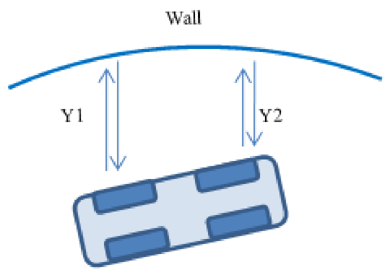

Fig. 12 Slip case

The sensor measures Y1, Y2 and changes the angular velocities of the left and right motor based on this measured value.

In case of a mile slip case, as shown in Figure 13, increase the angular velocities of the right motor to enter the specified range. And with sensor data, we updated the Y1 and Y2 figures and employed the new algorithm to adjust the angular velocity.

In the case of excessive slip (Figure 14), the new algorithm was used because it was impossible to correct the posture in a mild way(Figure 13).

If slip occurs unexpectedly with the reactor flange and the slip accumulates, it may deviate the desired path and require rapid postural correction.

To compensate posture of the mobile robot in excessive slip case, it moves backward until the value of the laser sensor is within the defined range using speed control of the left and right wheels. After moving backward, it moves forward again to drive with keeping it within the defined range.

The slip was calibrated using laser sensors in case of mild and excessive cases. This brought the slip ratio as close to zero as possible in Equation 5,6 so that it could travel on the desired path in an ideal manner, such as Equation 1-3. The slip cannot be completely removed, but it has improved its driving ability by continuously reducing its error.

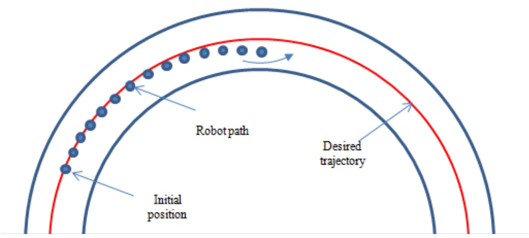

Fig. 13 Mild slip case

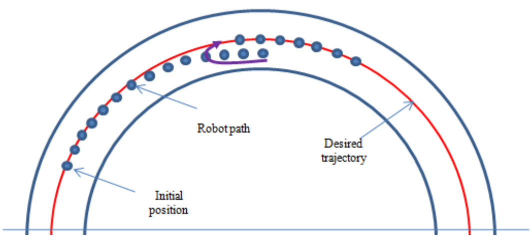

Fig. 14 Excessive slip case

This new control algorithm make it smooth driving by using the correlation of the numerical values from the sensor at the time of long distance travel.

3.2 Positioning

Another sensors are installed under the robot to confirm whether it is correctly located in the hole to be cleaned. If the gripper or brushing module is lowered without re-checking, it can crash the surface of the reactor flange and surface of the reactor may be damaged. So for safety's sake, when the mobile robot is driving, the stop point is detected by sensors. We checked the abnormal position of the robot by using four sensors to detect the position of the stud hole.

Four sensors were attached to the bottom of the robot to detect its arrival at the hole center position as the robot moved, and three or more of the four sensors were required to identify its arrival at the center position of the hole. According to the driving sensors, the robot is kept from being skewed. While the robot is driving without being excessively skewed, the hole sensors point to the bottom of hole. Positioning can be accurately maintain with the combination of hole sensors and driving sensors. When two sensors are operated, the gripper cannot be operated(Fig.16), and three or four sensors are operated to activate the gripper to complete the positioning(Fig.15).

If the mobile robot is correctly located in the reactor stud hole position, the gripper is operated. In this case, the four sensors mounted on the robot are facing into the hole bottom and the robot is in the correct position.

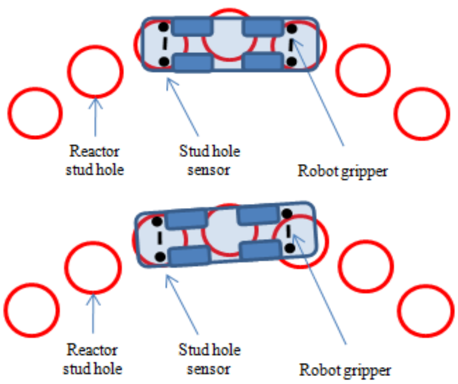

Fig 15 accurate position (4 sensors(upper), 3sensors(lower))

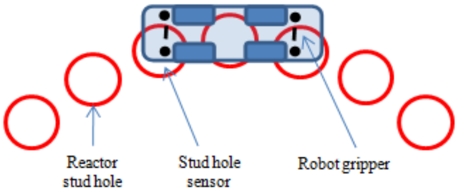

Fig. 16 inaccurate position(2 sensors)

If the mobile robot is incorrectly located in the reactor stud hole, the gripper is not operated. In this case, the sensor detects the reactor flange, not the hole bottom, and the robot is not in the correct position (Fig.16). At this time, the speed of the robot's left and right wheels is changed by a new algorithm to find the correct posture. In this case, the left and right motors are rotated in the opposite direction. The robot moves so that more than three sensors face into the hole. As such, the new algorithm was established to correct accumulated errors caused by slip. Using a driving sensor and a hole sensor, the robot can clean while maintaining the driving distance and angle.

4. Performance

As shown in figure 17, the mobile robot was installed above the reactor vessel in the NPP. The driving and cleaning performance and control algorithm of mobile robot were verified.

Driving was carried out on the top of the reactor stud holes. It rotated 360 degree smoothly without any problem. There was some slips in some sections. As shown in Figure 18, the robot started from position ①. Slip caused a slight deviation from the desired path due to the accumulation of error. In case of excessive slip (position ②) the robot moved backward to find the desired path, moved to a given range, and then moved forward again by the new control algorithm. In the case of mild slip (position ③) the left and right wheel speeds were controlled to reduce error and it goes back to the desired path.

The same result was obtained by driving in both clockwise and counterclockwise directions.

Even if there was offset, there was no difficulties because of the new algorithm. The new algorithm make the mobile robot move backward/forward to readjust the position of the mobile robot.

The removal of anti-seize agent and foreign materials was carried out while spraying the cleaning agent. Due to centrifugal force caused by rotation of the rotating shaft, the cleaning performance by the brushes extended in radial directions was excellent. The cleaning process was optimized by readjusting brushing times and the amount of injection of the cleaning agent. It was confirmed that foreign materials were removed through the optimized process.

Various interlocks were checked during driving and cleaning process. The grippers are prohibited during driving, and vice versa. After gripper operation, cleaning process is performed. Therefore, it was confirmed the stability of driving, hole sensing, gripping operation, optimal cleaning conditions, sequence control and various interlock functions.

We could save working hours by using automatic robot with new algorithm. So, the radiation exposure is reduced tremendously.

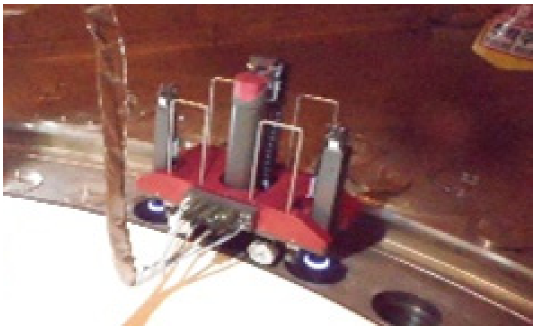

Fig. 17 Driving of mobile robot

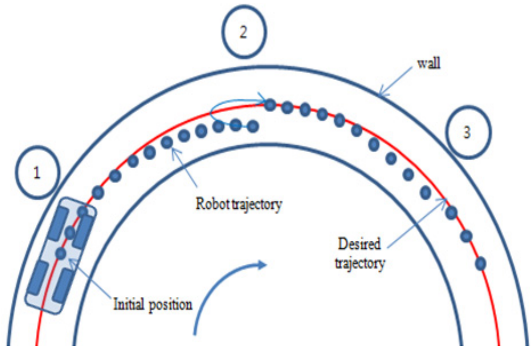

Fig. 18 Result based on proposed method

5. Conclusion

The NPP reactor stud holes may be stuck due to high temperatures, high pressure, prolonged engagement, and load changes from pressure changes in the reactor.

A threaded surface is required to remove any foreign materials that may exist between studs and holes. We tried to improve the working efficiency by using mobile robot rather than manually cleaning in high-radiation areas. Location recognition of a mobile robots is generally based on odometry, but as the mileage increase, positional errors accumulate due to slippage.

In order to eliminate cumulative errors and ensure stability of driving, new control algorithms were utilized. We developed the new algorithm that utilizes a distance sensor to control the mobile robot so that it does not get out of the way and to find holes to be clean.

Through field application, the driving performance and cleaning performance were verified and the excellence of control algorithm was also verified.

References

(1) Lamon, P. and Siegwart R., 2003, “3D Odometry for Rough Terrain towards Real 3D Navigation: Towards Real 3D Navigation,” *Proc. of the IEEE Robot Autom.*

(2) Borenstein, J. and Feng, L., 1996, “Gyrodometry: A New Method for Combining Data from Gyros and Odometry in Mobile Robots,” *Proc. of the IEEE Robot Autom.*, pp. 423-428.

(3) Yi, J., Zhang, J., Song, D., Jayasuriya, S., 2007, “IMU Based Localization and Slip Estimation for Skid Steered Mobile Robots,” *Proc. of the IEEE Int IROS*, pp. 2845-2850.

(4) Iossaqui, J. G., Camino, J. F., Zampieri, D. E., 2011, “A Nonlinear Control Design for Tracked Robots with Longitudinal Slip,” *Proc. of IFAC,* Volumes, 44(1), pp. 5932-5937.

(5) Ojeda, L., Cruz, D., Reina, G., Borenstein, J., 2006, “Current Based Slippage Detection and Odometry Correction for Mobile Robots and Planetary Rovers,” *IEEE Trans. on Robotics*, Volumes, 22(2), 366-378.

(6) Sutoh, M., Iijima, Y., Sakakieda, Y., Wakabayashi, S., 2018, “Motion Modeling and Localization of Skid Steering Wheeled Rover on Loose Terrain,” *Int. J Robot Autom.,* Volumes, 3(4), 4031-4037.

(7) Lamon, P., & Siegwart, R., 2004, “Inertial and 3D Odometry Fusion in Rough Terrain towards Real 3D Navigation,” *Proc. of the IEEE IROS*, pp. 1716-1721.

(8) Endo, D., Okada, Y., Nagatani, K., Yoshida, K., 2007, “Path Following Control for Tracked Vehicles Based on Slip Compensating Odometry,” *Proc. of the IEEE IROS*, pp. 2871-2876.

(9) Lee, K.M., Lim, D.K., Kim, H.G., Suh, B.S., 2005, “A Wall Following Method of Mobile Robot for Mapping,” *Proc. of the KIEE*, pp.102-105

(10) Choi, I. K., Kim, B. S., Lee, E. H., Jung, D. M., Hong, S.H., 1993, “The Method of Following Wall with the Motorized Wheelchair for the Disabled,” *Proc. of the KOSOMBE*, pp. 44-47

(11) Kim, S. J., Lee, J. W., Lee, C. G., 2002, “Driving Environment Recognition and a Simple Wall Following Algorithm for AGV Using Sonar Sensor,” *Proc. of the KIEE,* pp. 2337-2340.

(12) Yoon, J. W., Hong, S. K., 2000, “Following a Wall by an Mobile Robot with Sonar Sensors and Infrared Sensors,” *Int J Control Autom*, pp.1201-1204

(13) Prayudhi, L. H., Widyotriatmo, A., Hong, K. S., 2015, “Wall Following Control Algorithm for a Car-like Wheeled Mobile Robot with Differential Wheels Drive,” *Int J Control Autom*, pp.779-783.