International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I11P214

Volume 70 Issue 11, 138-143, November 2022

Original Article

Study of Wall Climbing Robot through the Simulation of Multi-Body Dynamics

Yeon Taek OH

School of Mechanical Engineering, Tongmyung University, Busan, Korea

Corresponding Author : yeonoh@tu.ac.kr

Received: 09 August 2022 Revised: 06 November 2022 Accepted: 11 November 2022 Published: 26 November 2022

Abstract - *This paper studied a robot that allows the exploration platform used for ship surfaces and large steel structures to drive on the wall. Regarding the wall-driving robot, this study proposed a stable operating structure even with the rapid change in the slope of the ship's surface. Wheel-based operating methods are challenging to drive flexibly on curved surfaces. Therefore, the robot was designed to have a rotating joint in the center of the driving robot. The arrangement of wheels is an essential aspect of this structure. They must overlap each other so that the robot wheels can intersect when viewed from the side view. The wheel also serves as a tool to attach to the wall with a circular neodymium magnet. The necessary magnetic force was proposed based on the conditions identified through dynamic modeling. Important factors required for magnetic force setting include platform weight, the angle between the ground and slope, and friction coefficient. Based on the analysis results, the platform was not slid and remained attached to the steel sheet.*

Keywords - *Exploration robot, Magnetic force, Wall-climbing, Mechanism, Maxwell analysis.*

1. Introduction

Robots were developed to enhance operations and to make them do simple tasks instead of humans. Thanks to the application of various robot structures and control theories, they are widely used in industrial fields, such as assembly processes requiring precision and operational environments deemed difficult for humans to access.

Currently, the scope of their applications is being further expanded to include robots designed to be employed in maritime or submarine areas, which are being developed. The primary purpose of robots used in this environment is to replace humans in exploring the areas. These exploration robots secure operational efficiency and safety during operations dangerous for humans. Those being utilized and developed in various fields aim to secure safety, prevent safety-related accidents, and enhance operational efficiency for human workers.

Generally, exploration robots are developed per specific operational environment. Among them are wall climbing ones, which climb the inclined plane of a large steel structure, targeted to be explored. The currently developed wall-climbing robots either run on wheels or are tracked, and in some exceptional cases, they are biped or quadruped. [1,2,3,4] An operating system of the continuous track is difficult to use in a narrow and curved environment similar to a ship's interior due to the continuous track's structure. It is required to minimize the size of the platform of the climbing robots to overcome such a disadvantage, but difficulties in reducing the size due to the structure of the track pose a limitation in its application to the interior of ships.[5]

Walking locomotion is beneficial to adapt to topographic changes but requires a complicated control system based on real-time kinetic calculations, posing limitations in its application to narrow environments such as ships.

This paper studied a structure that enables robots to climb a wall utilizing the adhesive force of magnets for their development based on the magnetic force so that they can be used for climbing steel structures, such as ships, and exploring their interior. In addition, it proposes applying a mechanism that guarantees smooth movements on a stiff slope closer to vertical as well as a wheel structure consisting of magnets for the locomotion mode. Furthermore, changes witnessed in the body of the robot while on the move were compared based on driving tests and simulation

2. Structure of wall-climbing robots

A structure of wall-climbing robots will be proposed to ensure that they not only climb a wall but are capable of mounting to and stably moving on a vertical plane.

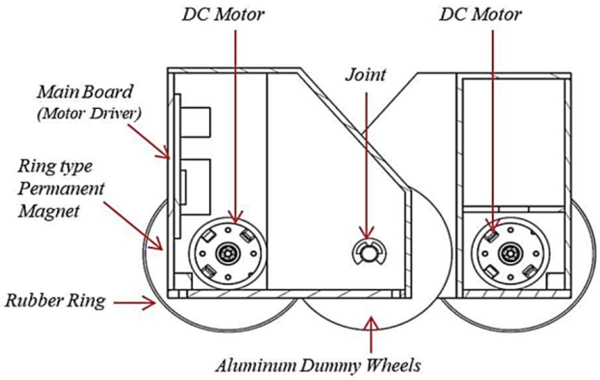

Fig. 1 Structure of wall climbing Robot

As shown in Fig. 1, it is not in an integral structure but adopts an axis of rotation with two modules that rotate as shown in the figure to ensure stable mounting onto the wall and wheels for locomotion. Their center of gravity (COG) is designed to be placed on the axis of rotation and in the center of the robot to ensure stable movement.

COG is located in the center by arranging the parts required in a robot accordingly. Auxiliary wheels are adopted around the rotation joints to guarantee the smooth movement of the robot and to serve as an auxiliary means to adapt to changes in geographical features. The axis of rotation of the platform is designed to rotate up to 40° counterclockwise to a point where both wheels come in contact with one another clockwise. Both wheels on the front and rear are attached with ring-type magnets, which generate repulsive force to ensure that they are not attached due to magnetism while moving.

The auxiliary wheels, made of aluminum, a non-magnetic material, are used to prevent them from being interfered with by magnetic force. They are introduced to ensure stable mounting to and movement on the vertical slope, as shown in Fig. 2 and Fig. 3. The front and rear wheels on the body are connected to a motor so that they operate independently and have a small turning radius when they rotate. Furthermore, rubber rings are placed on the outside of the magnetic wheels to increase friction between the robot and the surface that it is on.

Fig. 1 shows the structure of the wall-climbing robot, magnets, and auxiliary wheels.

The arrangement of wheels on the moving robot is a crucial factor as it affects its driving performance when it overcomes an obstacle. When mounting onto a wall, as shown in Fig. 2, the wheels should be arranged to overlap with one another. It is to ensure that the lower part of the robot's main body does not touch the obstacle, as demonstrated in the right picture of Fig. 3.

When the lower part of the body comes in contact with the obstacle, it affects its driving performance. Therefore, an intersection point, formed as the wheels overlap, should be placed closer to the bottom of the body when viewed from a side view. Upon the arrangement of the wheels reflecting the above aspects, their size determines that of the body. This determines the range of allowable weight, which leads to the selection of magnets used for the wheels.

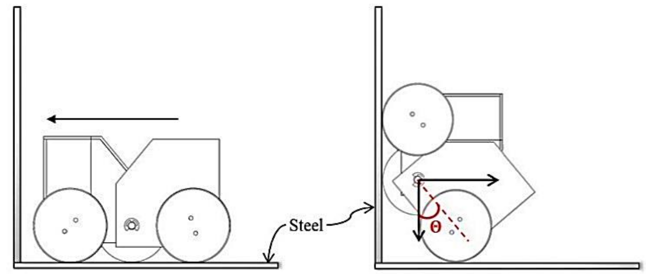

Fig. 2 Adaptation mechanism by inclined plane (Up)

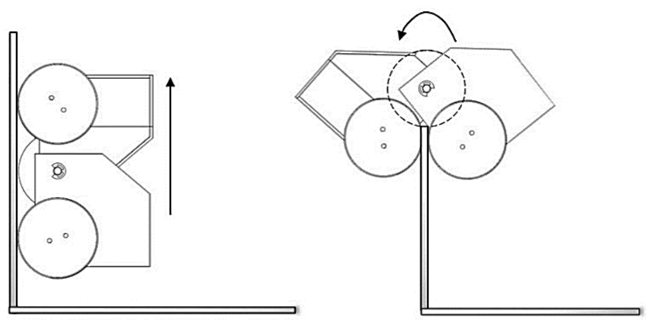

Fig. 3 Adaptation mechanism by inclined plane (Down)

To ensure stable movement of the robot on the wall, a magnetic force is required to make it adhere to the wall while preventing it from slipping.[5]. Fig. 4 depicts a free-body diagram to express the magnetic force required for the robot to avoid a fall or slip from the wall in a formula. Here, when the forces working in the x and y directions remain in balance, the robot sticks to the slope without moving, as defined in the formulas indicated in equations (1) and (2).

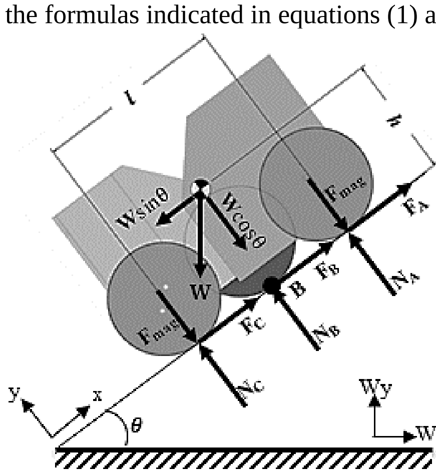

Fig. 4 Free Body Diagram for Wall Climbing Robot.

Here, W, B, l, h, and θ refer to the weight of the robot, center of rotation, wheel offset, and offset between the driving surface and center of rotation, respectively. Fmax, FA, FB, FC, NA, NB, and NC also signify magnetic force, frictional force, and normal force.

$$\sum F_x = F_A + F_B + F_c - WSin\theta° = 0 \quad (1)$$

$$\sum F_y = N_A + N_B + N_c - WCos\theta° - F_{mag} = 0 \quad (2)$$

In equation (2), $4F_{mag}$ refers to the magnetic force of the four magnets. It is translated to the minimum magnetic force required for the body to adhere to the wall and to produce a formula to calculate it; the relations between the normal force and the coefficient of friction, used in equation (1), are shown in equation (3)

$$4F_{max} \geq W\frac{Sin\theta}{\mu} \quad (3)$$

3. Driving Environment and Testing

The driving environment in which a wall-climbing robot operates should be a steel structure consisting of materials through which a magnetic force can flow. In addition, it needs to be driven at a slope higher than 90 degrees to guarantee that it does not deviate from the designated path but moves as planned. Against this backdrop, an initial test was carried out on a steel structure with a vertical slope, as shown in Fig. 5. A driving environment was created where the slope was made closer to a right angle at the bottom of the steel structure.

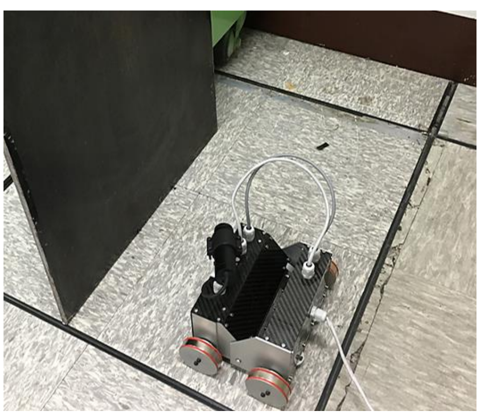

Fig. 5 Wall Climbing Robot

Fig. 5 shows a wall-climbing robot produced based on the design specifications. When the robot was placed on the steel frame during the initial test, it remained attached in a stable manner. Furthermore, another experiment using the suggested structure, in which the robot was made to mount to the vertical slope from the ground, confirmed that it smoothly moved onto the slope.

First, Fig. 6 shows how the robot was mounted onto the vertical slope. While it was moving onto the steel plate, it was observed that a section where the robot accelerated due to the magnetic force before it came in contact with the steel structure, and later it stayed attached to the surface while moving without being broken off. It was also confirmed that the robot remained adhered to the surface while standing without being slipped by the weight. When the rubber rings were removed from the wheels, in this case, it was slipped downward, which signifies a significantly low coefficient of friction between the coating material of the permanent magnets and the surface of the vertical plane. Therefore, it is necessary to maintain a certain coefficient of friction to prevent any slip by adding material, such as rubber or silicon, to the wheels. Furthermore, it is required to design a controller capable of regulating the speed of the motor by attaching an encoder to maintain a certain speed in a section where the robot is made to accelerate by the magnetic force before it touches the surface of the steel plate on the slope.

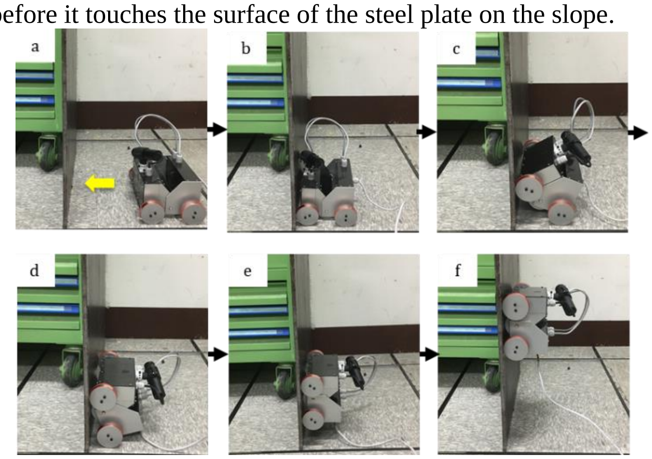

Fig. 6 Entering the Vertical Slope of Wall Climbing Robot (a, b: entering, c, d, e: sticking, f: driving)

Next, the robot was simulated to move along a surface whose inclined angle significantly shifted. Fig 7 & 8 indicate how the robot overcame the sudden change in the inclined angle while moving vertically or horizontally.

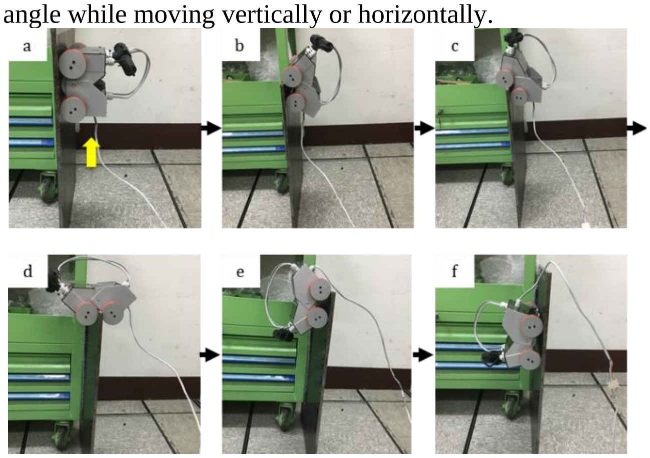

Fig. 7 Overcoming Vertical Obstacle of Wall Climbing Robot (a, b: entering, c, d, e: overcome, f: driving)

When it was being operated on a surface that posed a sudden change in its angle, the robot, based on the design specifications, was folded easily and moved over to the other side without deviating from the driving path. At that moment, however, if the robot drove diagonally across the vertical plane, not in parallel with its boundary, and one of its wheels touched the boundary, it fell off the wall. This makes the wheels positioned so that it is impossible to maintain their constant adherence to the steel structure. To prevent this, the wheels should be controlled to move in parallel with the boundary of the vertical plane when overcoming an obstacle to maintain their consistent adherence.

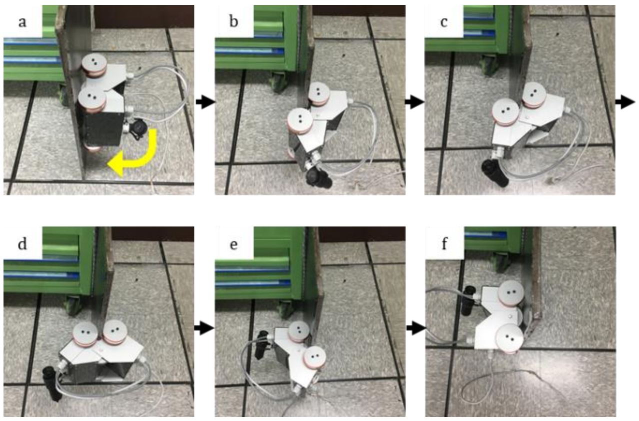

Fig. 8 Overcoming Horizontal Obstacle of Wall Climbing Robot (a, b: entering, c, d, e: overcome, f: driving)

In addition, when the robot drove vertically after moving over the boundary, dummy wheel(s), located in the central axis of revolute joints, was found to be off the driving surface, as shown in Fig. 7(f).

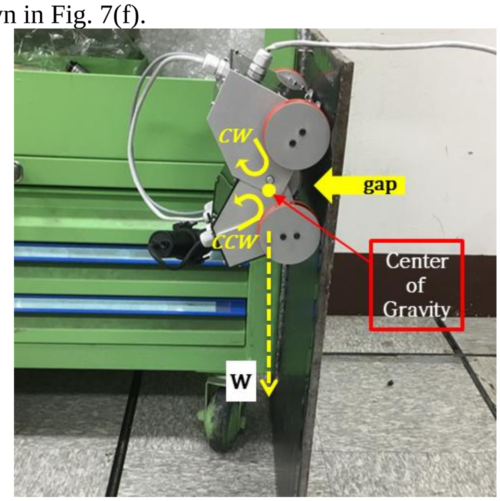

Fig. 9 Vertical Driving of Wall Climbing Robot

Fig. 9 shows an enlarged version of Fig. 7(f) that depicts the driving path of the robot. As demonstrated in Fig. 9, while the robot moves downward, the non-magnetic dummy wheels connected to the central joints of its body are off the steel plate. A close look at the structure of the wall-climbing robot indicates that its COG is higher than the wheels' axle. Therefore, a moment triggered in the front body of the robot by the weight (W) is generated counterclockwise from the axle of the front wheels, which is assumed to lead to the flexible joints of the robot being extended, creating a gap between the dummy wheels and the steel plate.

To delve into such a phenomenon, kinetics simulation software was employed for comparison. Such simulation software is utilized in various industries to verify the design of a product and optimize its parts upon the completion of its design before the production of a prototype.

Numerous types of virtual simulation software can be divided into the structure, kinetics, and thermal/fluid areas. When it comes to product design, structural analysis is an essential factor as it calculates stress applied to the product and its deformation to decide it is material and shape. For the analysis, weight applied on the product and boundary conditions should be entered in the structural analysis software, and generally, the results of an experiment are considered appropriate for the purpose. In the case of a system that is kinematically connected in a complex manner, it is not easy to define the effective weight and boundary conditions. To resolve such difficulty, this study decided to apply the dynamic load from the dynamic characteristics generated from the kinetics and structural analysis software for the analysis. For the kinetics and structural analysis software, Recurdyn was chosen. Recurdyn is a software program that interprets a response from the system in the time domain when a force is applied to the rigid body system connected to kinetic constraints. Primarily Implicit Integrator based on Recursive Formulation with a relative coordinate system was used. Fig. 10 shows the simulation results.

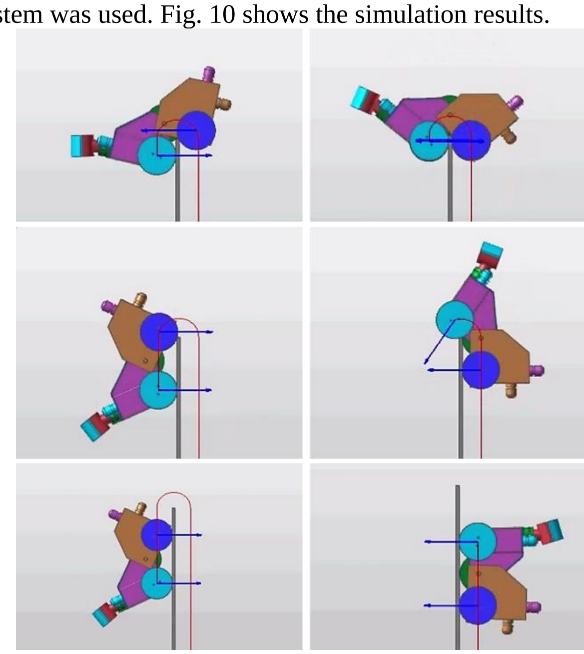

Fig. 10 Simulation Result of Wall Climbing Robot

To avoid such a problem, the torsion spring was adopted on the joint of the robot, as shown in Fig. 11, to apply torque

(τ_s) in an opposite direction from which the body rotates to enhance a gap between the dummy wheels and the steel plate, created while moving downward.

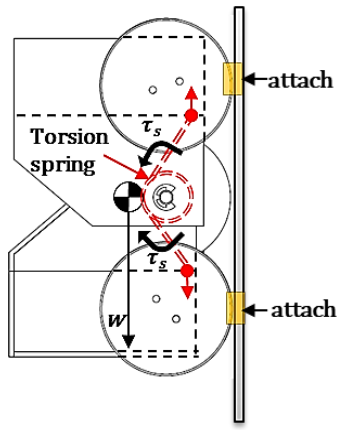

Fig. 11 Driving Pose Improvement with Torsion Spring

In this case, it is necessary to maintain a torque larger than the moment caused by COG but smaller than the one triggered by the normal force of the magnetic wheels. When a torque more extensive than the normal force of the magnetic wheels is applied on the joints of the moving robot, its force acts in the opposite direction from the adhesive force, making the robot fall off the surface. Reflecting on the abovementioned aspects, the robot's structure needs improvement.

4. Conclusion

A mechanism that guarantees stable driving of the robot in the face of a sharp change on the inclined plane was proposed. It enables a moving robot to respond flexibly to a sudden change in the inclined angle as it mounts to the slope, thanks to the joints placed on the center of the body. An actual robot experiment confirmed that it moved over a thin steel plate stably without being derailed from the path.

This structure with a permanent magnet and motor selected based on the adhesive force modelling on the inclined plane is what this study has proposed. It was materialized for an experiment to confirm that the robot could drive on the slope and maintain the adhesive force without falling off even when it moved on a very steep slope, thanks to the joint structure.

The adhesive force was suggested in the form of a formula to select a magnet required for the design of the wall-climbing robot using the magnetic force. The adhesive force based on the magnetic one should be reflected in the magnet selection and in calculating the torque required for the wheels.

However, when the robot moved downward on the slope, the joints of the dummy wheels located in the center of the robot were found to stay off the surface. The gap created between the dummy wheels and the surface while moving downward on the vertical slope was confirmed in a simulation, which led to a solution that involved using a torsion spring on the joint to enhance the robot's structure. An additional study on power and speed control required for the robot's movement is planned to be carried out by modelling its driving performance on a wall depending on its inclined angle.

Acknowledgments

This Research was supported by a grant from Tongmyong University Innovated University Research Park(I-URP) funded by Busan Metropolitan City, Republic of Korea. (IURP2201) and by the Tongmyong University Research Grants 2021(2021A030).

References

[1] Kwon S. D, Kim S. J, Kim S. Y, and Kim S. H, “Design of Wall-Climbing Mobile Platform by Modeling of Attachable and Traction Force,” in Proceedings of the *2010 Fall Conference of The Korean Association of Immunologists, Korean Society of Precision Engineering*, pp. 239-240, 2010.

[2] Choi. H. R. and Lee. J. H., “Development of Wall Climbing Robot,” in Proceedings of the *1999 Spring Conference of The Korean Association of Immunologists, Korean Society of Precision Engineering*, pp. 3-9, 1999.

[3] Kim H, Seo K, Kim J and Kim H, “Design of Tracked Wheel Mechanism for Wall Climbing Robot,” in Proceedings of the *2010 Fall Conference of the Korean Association of Immunologists, Korean Society of Precision Engineering*, pp. 215-216, 2010.

[4] Park S. H, Seo K. J, Choi J. R, Kwon D. H, Bang J. H and Kim S. G, “Development of the Wall Climbing Robot Using New Mechanism,” in Proceedings of the *2016 Fall Conference of the Korean Association of Immunologists, Korean Society of Precision Engineering*, pp. 150-151, 2016.

[5] Yi H, Kim E and Han S, “Guideline for the Design of Wall-Climbing Mobile Robot Using Permanent Magnetic Wheels,” in Proceedings of the *2002 Fall Conference of The Korean Association of Immunologists, Korean Society of Precision Engineering*, pp. 548-553, 2002.

[6] Bradley A. M, Feezor M. D, Singh H and Sorrell F. Y, “Power System for Autonomous Underwater Vehicle,” *IEEE Journal of Oceanic Engineering*, vol. 26, no. 4, pp. 526-538, 2001. Crossref, https://doi.org/10.1109/48.972089

[7] Daijun X, Xueshan G, Xiaobing W, Ningjun F, Kejie L and Koki K, “Suction Ability Analyses of a Novel Wall Climbing Robot,” *Proceedings of IEEE International Conference on Robotics and Biomimetics*, pp. 1506-1511, 2006. Crossref, https://doi.org/10.1109/ROBIO.2006.340152

[8] Roan Van Hoa, Nguyen Duc Dien and Lai Khac Lai, "Research and Apply Deep Reinforcement Learning Technology to Control Mobile Robot," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 8, no. 4, pp. 30-35, 2021. Crossref, https://doi.org/10.14445/23488379/IJEEE-V8I4P106

[9] Han S. C, Lee J. Y and Kim J. H, "Design of Hybrid Magnet Wheels Using 3d Finite Element Analysis for Wall-Climbing Robot," *Journal of the Society of Naval Architects of Korea*, vol. 47, no. 1, pp. 88-89, 2010. Crossref, http://dx.doi.org/10.3744/SNAK.2010.47.1.088

[10] Roan Van Hoa, L. K. Lai and Le Thi Hoan, "Mobile Robot Navigation Using Deep Reinforcement Learning in Unknown Environments," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 7, no. 8, pp. 15-20, 2020. Crossref, https://doi.org/10.14445/23488379/IJEEE-V7I8P104

[11] McEwen R. H, Thomas D, Weber D and Psota F, "Performance of an AUV Navigation System at Arctic Latitudes," *IEEE Journal of Oceanic Engineering*, vol. 30, no. 2, pp. 443-454, 2005. Crossref, https://doi.org/10.1109/OCEANS.2003.178387

[12] Nicholson J. W and Healey A. J, "The Present State of Autonomous Underwater Vehicle (AUV) Application and Technologies," *Marine Technology Society Journal*, vol. 42, no. 1, pp. 44-52, 2008. Crossref, https://doi.org/10.4031/002533208786861272

[13] Nguyen Duc Dien, Nguyen Duc Duong, Vu Anh Nam and Tran Thi Huong, "Building Environmental Awareness System for Mobile Robot Operating in Indoor Environment on ROS Platform," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 8, no. 1, pp. 32-36, 2021. Crossref, https://doi.org/10.14445/23488379/IJEEE-V8I1P106

[14] OH Y. T., "Evaluation of Joint Driving Torque and Finite Element Analysis in Articulate Robot Through the Simulation of Multi-Body Dynamics," *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 11, pp. 682-686, 2019. Crossref, http://doi.org/10.35940/ijitee.K1725.0981119

[15] OH, Yeon Taek, "Study of Wall Climbing Robot Having Magnetic Force," *Journal of the Korean Society of Mechanical Technology*, vol. 22, no. 6, pp. 1001-1005, 2022.

[16] Sibenac M, Podder T, Kirkwood W and Thomas H, "Autonomous Underwater Vehicles for Ocean Research: Current Needs and State of the Art Technologies," *Marine Technology Society Journal*, vol. 38, no. 2, pp. 63-72, 2004. Crossref, https://doi.org/10.4031/002533204787522848

[17] Song Y. K, Lee C. M, Koo I. M, Trong D. T, Moon H and Choi H. R, "Development of Wall Climbing Robotic System for Inspection Purpose," in Proceedings of *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1990-1995, 2008. Crossref, https://doi.org/10.1109/IROS.2008.4650885