Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 54-13 (2021) 339–344

Slip Detection and Compensation System for Mobile Robot in Heterogeneous Environment

Belyaev A.S., Brylev O.A., Ivanov E.A.

National Research Tomsk Polytechnic University, Tomsk, Russia
(Tel: +7913-840-3833; e-mail: asb22@tpu.ru).

Abstract: Research of the robot's motor currents during the motion across highly heterogeneous surface is considered in the paper. Dependencies between motor current and slip coefficient were obtained. The indirect variable, characterizing the wheels' torque, was introduced. The motion vector compensation system was implemented. The motion compensation vector is determined through the indirect torque characterizing variables. The robot's trajectory of motion with the implemented correction are presented. Obtained trajectories proved qualitative dependencies of the implemented system.

Keywords: Mobile robot, control system, terrain, slip detection, different environments.

1. INTRODUCTION

Heterogeneous natural conditions, such as dirt, snow, sand, grass etc. negatively affect robot's behaviour, while operating in such kind of environment. The impact of such conditions is observed in presence of robot's wheels' slip, which influences the movement of the robot. Its affection adds a crucial error while to the process of solving the navigation, localization and path-planning tasks. This happens due to impossibility of detecting the slip with encoders or other rotary sensors. Besides, operating in real conditions, where a single area may consist of areas of varying traversability. This aspect may create additional cumulative effects. Such impacts significantly increase the complexity of control systems, as it is important to understand not only where the robot is located, but also what kind of surface it is moving on and the way the robot should behave. Stuck and dip of wheels complicate the controlling process even more. With all of these effects the robot is required not only to complete the task, but understand the way of moving on the surface in order not to get stuck.

According to the mentioned, the mathematical models for robots, operating in natural conditions, are built. They determine the value of the impact of the surface and try to compensate that influence. There are several basic methods for implementation of such algorithms:

- based on physical values determination, such as slip;
- based on non-physical regularities, obtained mostly via artificial intelligence methods.

Both of these may be divided into 2 categories:

- using segmentation of the surface;
- without segmentation, building a generalized motion model.

In papers (Ojeda et al., 2006; Reina et al., 2006) authors computed physical dependency between motor current and wheel slip for robot, moving across sandy-stony surface. Obtained information was applied to the control system for wheel slip compensation. That allowed to correct the trajectory of robot's movement greatly.

Authors of (Reina et al., 2006) used traversability classifier of the surface for robot motion. This classifier was based on robot's dynamic model and data from the sensors system (force sensor, inertia sensor, encoders, torque sensor). Determination of traversability is held via evaluating the force of motion resistance and the value of wheel slip, which are obtained from the sensor system.

In (Goswami & Padhy, 2018) wheel slip compensation during the motion is based on the kinematics of mobile robot and the regulator, based on Lyapunov function.

Papers (Quann et al., 2017, 2020a, 2020b) represent a method of evaluation of surfaces, based on energy consumption. This method is applied for correction of robot's motion in natural environment. The energy consumption model is built via Gaussian process.

Authors of (Andrakhanov & Belyaev, 2017, 2018) built localization models with the help of neural networks, based on Group Method of Data Handling (GMDH). Input parameters included data from gyroscopes, accelerometers, current sensors and encoders. Output data from the model was used for correction of robot's motion while moving across some highly heterogeneous surface. Besides, the authors compared the operation of two kinds of models: with preliminary classification of different surfaces and without it.

Paper (Ward & Iagnemma, 2008) represents wheel slip detection of a mobile robot through evaluation of forces, applied to the wheel. Data, obtained from sensor system, including inertia sensors and encoders, was used for that. Such model allowed detecting not only slip, but also determine, whether the wheel got stuck.

Presented approaches show high accuracy of wheel slip detection and surfaces classification, when robot's size is far smaller, than the size of the surface. Operating in conditions, when the size of the surface is compatible to the robot's size

10.1016/j.ifacol.2021.10.470

(Andrakhanov & Belyaev, 2017, 2018) or in the places, where robot meets a sharp transition from one surface type to another (Quann et al., 2017), researchers face a variety of problems. The algorithms start gaining error, which leads to the negative effects. Besides, the problem of maximally effective motion through the surface remains unsolved. This work represents the study of robot's motion through a highly heterogeneous surface and building a control system for robot, moving across it.

2. DATA ANALYSIS

2.1 Test site

Test site is demonstrated and described in works (Andrakhanov & Belyaev, 2017, 2018). It is comprised of surfaces of various traversability and size. Each piece of the test site includes two parts: internal and external. External part imitates the influence of immersion. It can be of two types: firm (without immersion) and soft (with immersion). External part of the surface may be of eight types, which are distinguished by color. Three main types, which differ in traversability, are highlighted for the research:

Table 1. Main types of the test site surface.

		
Type 1 – surface with low traversability, with immersion	Type 2– surface with medium traversability, without immersion	Type 3 – surface with high traversability, without immersion

Mobile robotic platform FESTO Robotino is used for the research. It has an ArUco marker, placed on its top side, which is necessary for determination of robot's position and angular orientation on the surface. Position detection is based on computer vision algorithms. Image of the test site and the robotic platform is presented in figure 1.

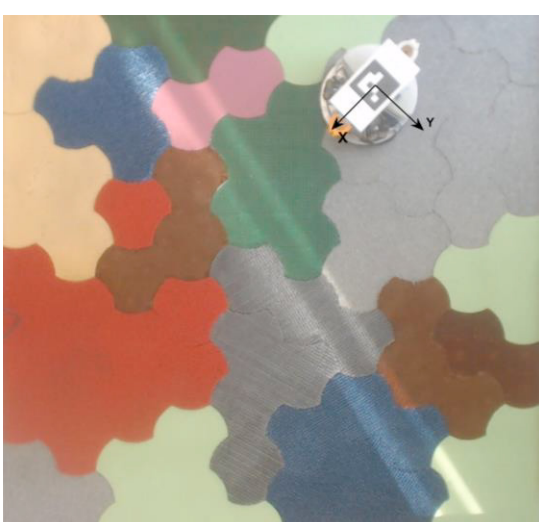

Figure. 1. Mobile robotic platform on the test site with heterogeneous surface

2.2 Raw data analysis

On the analogy with the work (Ojeda et al., 2006) the main task of presented research is detection of wheel slip of mobile robotic platform. This detection is based on the data, obtained from current sensors. The ratio of real angular velocity of the wheel ω_{eff} to the angular velocity of the wheel, obtained from the encoder ω_{act} was set as the slip coefficient s:

$$s = 1 - \frac{\omega_{eff}}{\omega_{act}}$$

Determination of the real angular velocity of robot's wheels is processed in several steps. First of all, robot's coordinate increments and angular increment $\Delta X, \Delta Y, \Delta\theta$ in its local coordinate system were obtained through the computer vision algorithms.

Based on that data, with kinematics transformations for 3-wheeled omni-platform (Gfrerrer, 2008; Indiveri, 2009), real wheels' angular velocity ω_{eff} are obtained:

$$\begin{pmatrix} \omega_{eff1} \\ \omega_{eff2} \\ \omega_{eff3} \end{pmatrix} = \frac{60 \cdot k_{red}}{2\pi \cdot R} \begin{pmatrix} -\sin\left(\frac{\pi}{3}\right) & \cos\left(\frac{\pi}{3}\right) & L \\ -\sin(\pi) & \cos(\pi) & L \\ -\sin\left(\frac{5\pi}{3}\right) & \cos\left(\frac{5\pi}{3}\right) & L \end{pmatrix} \cdot \begin{pmatrix} \frac{\Delta X}{\Delta t} \\ \frac{\Delta Y}{\Delta t} \\ \frac{\Delta\theta}{\Delta t} \end{pmatrix},$$

where L is the distance between the center of the robot and the wheels (125 mm); R is the radius of the wheel (40 mm); k_{red} is the gear ratio (16).

For obtaining the dependencies, analogous with the (Ojeda et al., 2006), between motor current of a robot and slip coefficient, a number of experiments was held.

During the experiments motor current, wheel speed and robot's position were obtained. Speed parameters in local coordinates system of the mobile platform were set as control values:

- Along its local X axis: ± 100, 200, 300, 400 mm/s;
- Along its local Y axis: ± 100, 200, 300, 400 mm/s;
- Along its local X and Y axis: ± 100, 200, 300 mm/s.

Experimental data is presented in figure 2. Linear dependency was built according to the support vector machine (SVM) method.

Analyzing the obtained data, it is clear, that there is a huge dispersion. The reason for that is the influence of a highly heterogeneous test site. Besides, low clearance and robot's kinematics with omni-wheels affect the data greatly.

These effects make the problem of slip detection and autonomous navigation even more complicated. Mentioned effects, united, turn the resistance torque into a complex value with a significant nonlinearity. That is why using linear dependencies between current and slip coefficient is unacceptable in this case.

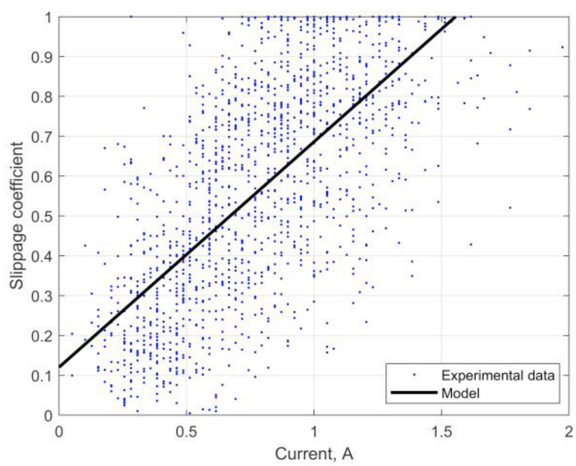

Fig. 2. Experimental data and the obtained relationship between current and slip coefficient

As one of the main factors, affecting the complexity of the task, is the heterogeneous test site, it was decided to carry out a number of analogous experiments on different types of the surface separately. Data, obtained during the experiments, is presented in figure 3. This data also has a significant dispersion, especially, when moving across the red surface (surface with low traversability and immersion effect). According to this data, the correlation between motor currents and type of surface, can be seen. This provides additional information about the type of the underlying surface.

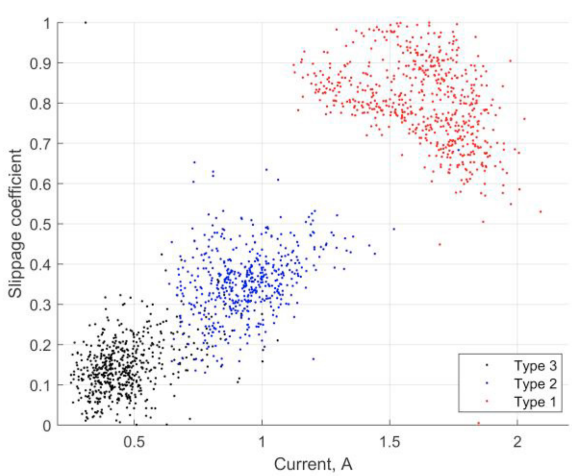

Fig. 3. Experimental data of robot's motion on different types of the surface separately

However, during the experiment it was found out, that while moving across highly heterogeneous test site (when robot's wheels are placed on different types of surface), mutual influence of various types of surface affects the data, obtained from the sensors system. As the result, the difference between wheels' currents is too small even on highly differing surfaces. That is why using this information for slip detection is impossible, as there is no possibility of determination and correction of the position and angular orientation of the robot. It does not allow computing the slip coefficient in a proper way.

Such an effect may be caused either by the construction of the test site, or by the construction of the robot (in particular, by the built-in current and speed controller and by low clearance).

During further investigations there was decided to make a transition from the current values to the toque characterizing static indirect variable M. This variable must include not only the motor current values, but also the assumed motor input value. It also must consider the wheel's speed, according to the encoders. This value is obtained through the formulas below:

$$M = \frac{U \cdot I}{\omega},$$

where U is the motor voltage, I is the motor current, ω is the angular velocity of the wheel. Motor voltage was calculated, according to the static dependency of the electric part of a DC motor:

$$U = I \cdot R + C_e \cdot \omega,$$

where R is the motor windings resistance, C_e is the electrical coefficient of the motor.

These characteristics allow considering the motor voltage and determining the labor intensity of motion across varying surfaces more precise. The same way as it was with the dependency between current and slip coefficient, there were built models, according to the obtained variables.

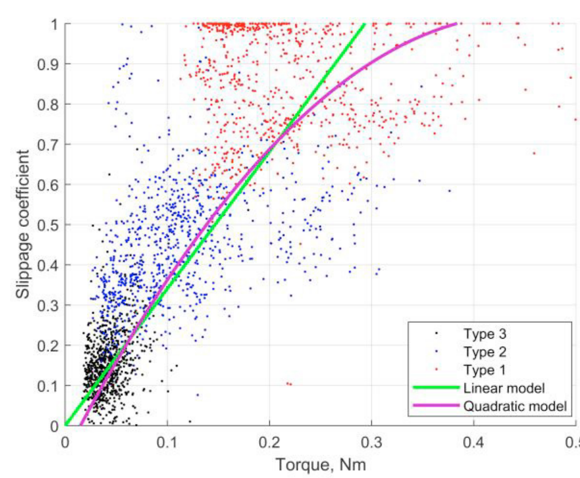

Fig. 4. Experimental data and calculated dependency between motor torque and slip coefficient

Both obtained models have significantly differ from experimental data. Furthermore, these models have similarities in most part of torque values. Therefore, any of these models may be chosen. So, the authors took linear model.

The motion resistance torque is a multifunctional variable. Therefore, the indirect variable M may be used for its initial assessment. However, obtaining results of a higher quality requires specifying the main components of the torque resistance of the surface. This requires preliminary data filtration using predictive models and consideration of the main motion parameters. However, for understanding of practical applicability of obtained dependencies, it was decided to validate them during the motion of the robot, which requires designing a control system.

3. COMPENSATION SYSTEM

3.1 Synthesis of slip compensation system

Variable M detection allows calculating the real robot's wheels' speed, using the models, calculated previously, and correcting the motion of the robot, according to the torque values. Motion correction includes a number of steps. The first step involves conversion of the torque of the wheels into the robot's motion forces in its local coordinate system. Such transformations are carried out via direct kinematics transform (Gfrerrer, 2008; Indiveri, 2009):

$$\begin{pmatrix} F_x \\ F_y \\ M_\Omega \end{pmatrix} = \frac{1}{R} \cdot \begin{pmatrix} -\cos(-\frac{\pi}{6}) & \sin(0) & \cos(\frac{\pi}{6}) \\ -\sin(-\frac{\pi}{6}) & -\cos(0) & \sin(\frac{\pi}{6}) \\ L & L & L \end{pmatrix} \cdot \begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix},$$

where L is the distance between the center of the robot and its wheels, M_1, M_2, M_3 are the calculated variables, characterizing the torques of the wheels, F_x, F_y are the motion forces of the robot, created by the motor, along the local coordinate system axes, M_Ω is the torque of the robot.

Then the vector of robot's deviation from the set direction $\{F_x' \quad F_y' \quad M_\Omega'\}$ is calculated, according to the initially set robot's speed vector. The obtained data is converted into the wheels' torque correction values $\{M_1^c \quad M_2^c \quad M_3^c\}$ via the kinematics transform:

$$\begin{pmatrix} M_1^c \\ M_2^c \\ M_3^c \end{pmatrix} = R \cdot \begin{pmatrix} -\sin\left(\frac{\pi}{3}\right) & \cos\left(\frac{\pi}{3}\right) & \frac{1}{L} \\ -\sin(\pi) & \cos(\pi) & \frac{1}{L} \\ -\sin\left(\frac{5\pi}{3}\right) & \cos\left(\frac{5\pi}{3}\right) & \frac{1}{L} \end{pmatrix} \cdot \begin{pmatrix} F_x' \\ F_y' \\ M_\Omega' \end{pmatrix}.$$

The calculated torque correcting values with the gain coefficients are set as an additional control signal for the wheel speed of a mobile robotic platform.

The distance, passed by the robot, and the rotation angle values are calculated, according to the dependencies between motor torques and slip coefficient, which were calculated previously. Using the calculated slip coefficient together with the wheels' speed ω_i data, where i is the wheel number, there may be calculated the wheels' speed ω_i', which influences the robot's motion. Using the already known direct kinematics equations, we calculate the linear wheels' speed and rotation speed of the robot $\{v_x', v_y', \Omega'\}$, including slippage, from previously obtained wheels' speed ω_i'.

$$\begin{pmatrix} V_x' \\ V_y' \\ \Omega' \end{pmatrix} = R \cdot \begin{pmatrix} -\frac{2}{3}\cos(-\frac{\pi}{6}) & \frac{2}{3}\sin(0) & \frac{2}{3}\cos(\frac{\pi}{6}) \\ -\frac{2}{3}\sin(-\frac{\pi}{6}) & -\frac{2}{3}\cos(0) & \frac{2}{3}\sin(\frac{\pi}{6}) \\ \frac{1}{3 \cdot L} & \frac{1}{3 \cdot L} & \frac{1}{3 \cdot L} \end{pmatrix} \cdot \begin{pmatrix} \omega_1' \\ \omega_2' \\ \omega_3' \end{pmatrix}.$$

Mobile robotic platform FESTO Robotino, already has a built-in wheel speed controller. Therefore, the external wheel speed and angular position controller was implemented for slip compensation. For that purpose, previously obtained values $\{v_x', v_y', \Omega'\}$ were submitted to the integrators. As the result, the robot's position, considering the slip, is obtained. These values are subtracted from the user's set values $\{x_s, y_s, \theta_s\}$, this difference is submitted to the controller's input. The described block diagram of robot control system, considering the slip, is presented in figure 5.

3.2 Control system tests

The test of control system was held on the heterogeneous test site, which is presented in figure 6. The rectangle are represented with the black arrows. The rectangle size is 900 mm by 400 mm.

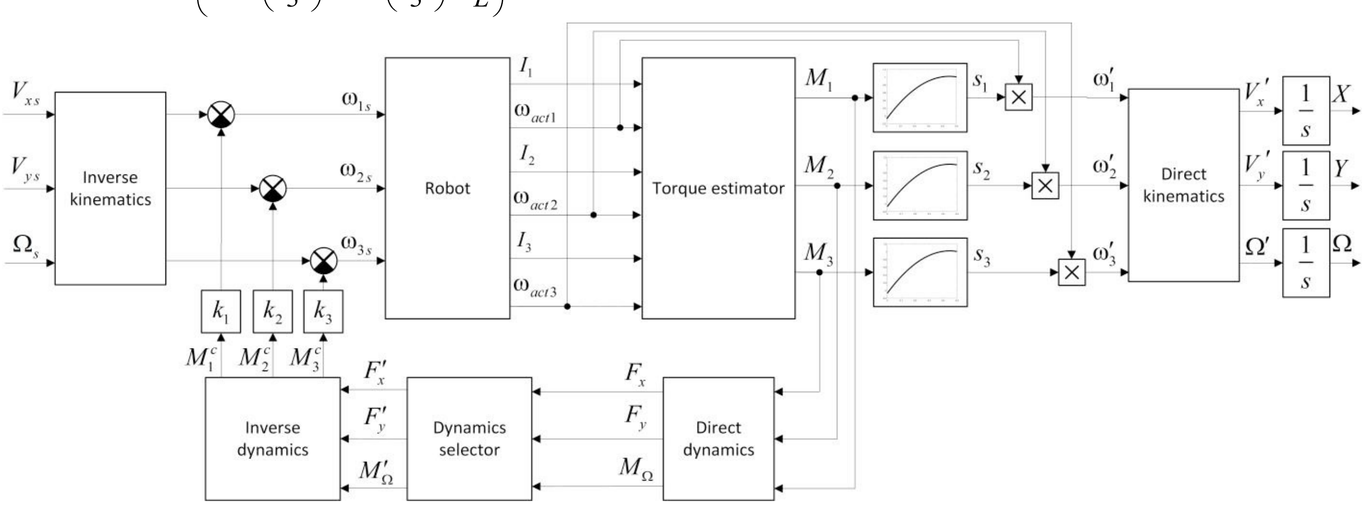

Fig. 5. Control system block diagram.

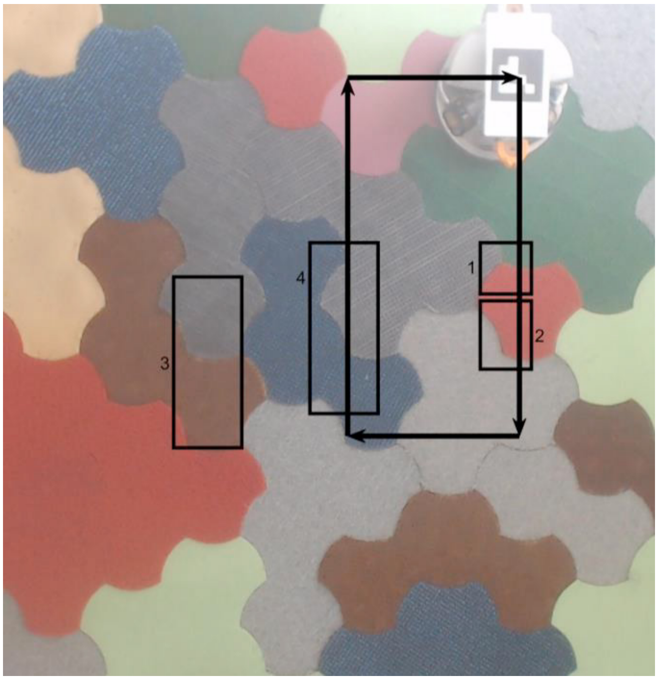

Fig. 6. Test site image

Three experiments results were compared through the test. The first experiment included using only the encoders' data (fig. 7, blue trajectory), the second experiment included the calculation of the distance, traveled by the robot, according to the slip coefficient models (fig. 7, green trajectory) and the third experiment was held with the torque correction (fig. 7, red trajectory).

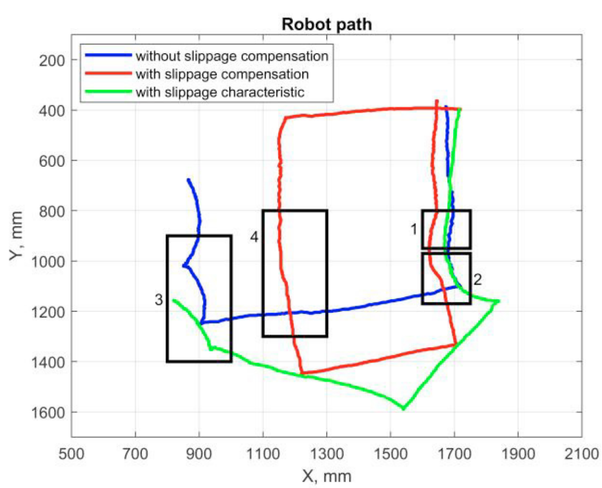

Fig. 7. Robot's motion trajectory across the heterogeneous test site

Figures 6 and 7 have four zones highlighted (squares with numbers), which influence the motion most. At the start the robot moves across the green surface, which has a firm top layer. In the first zone the robot's left wheel stands on the gray surface with high and soft relief and starts rotating to the left. After that, the right wheel appears in the red surface and gets into the second zone. Red surface, which is the hardest to pass, starts rotating the robot to the right. At this stage the compensation system stabilizes the wheels' torques, which decreases the deviation from the set trajectory. In the figure 7, in the second zone there may be seen, that the red trajectory is stabilized, unlike green and blue trajectories. Systems without stabilization curl in the second zone and therefore get into the third zone, where they almost get stuck. Robot in the zone 4, moving with the help of stabilization system, gets its wheels on the surfaces with varying height. This allows correcting its motion trajectory a bit.

Traveled distances for three types of system were compared for motion along the first side of the preset rectangle, which is 900 mm long. Using only encoder output values, robot traveled 760 mm, while using the slip models, robot traveled 940 mm, and 1031 mm with the compensation system. Using slip models allows reaching the destination. However, traveled distance calculation is still processed with the error. It results in robot passing distances, larger, then it was set.

According to the experimental trajectories, it is clear, that the implemented control system allows considering the influence of the physically heterogeneous surface on the robot's motion and allows correcting it.

4. CONCLUSION

The implemented method uses the indirect, characterizing wheel's torque, variable for robot's motion vector correction and calculating of the distance traveled. It considers the wheel's speed sensor and demonstrates qualitative dependencies during the robot's motion across highly heterogeneous test site. However, applying the obtained results to the industrial purposes requires consideration of the test site, affecting the dynamics of the mobile robotic platform, with respect to the multicomponent torque function. It also requires taking current position and spatial motion direction of the robot into account.

5. ACKNOWLEDGEMENTS

The research is carried out with the support of the Foundation for Assistance to Small Innovative Enterprises under contract № 16053GU/2020 dated 24.12.2020.

REFERENCES

Andrakhanov, A., & Belyaev, A. (2018). GMDH-based learning system for mobile robot navigation in heterogeneous environment. *Advances in Intelligent Systems and Computing*, *689*. https://doi.org/10.1007/978-3-319-70581-1_1

Andrakhanov, A., & Belyaev, A. (2017). Navigation learning system for mobile robot in heterogeneous environment: Inductive modeling approach. *Proceedings of the 12th International Scientific and Technical Conference on Computer Sciences and Information Technologies, CSIT 2017*, *1*. https://doi.org/10.1109/STC-CSIT.2017.8098846

Gfrerer, A. (2008). Geometry and kinematics of the Mecanum wheel. *Computer Aided Geometric Design*, *25*(9). https://doi.org/10.1016/j.cagd.2008.07.008

Goswami, N. K., & Padhy, P. K. (2018). Gain tuning of lyapunov function based controller using pso for mobile robot control. *11th International Conference on*

Industrial and Information Systems, ICIIS 2016 - Conference Proceedings, *2018-January*. https://doi.org/10.1109/ICIINFS.2016.8262954

Indiveri, G. (2009). Swedish wheeled omnidirectional mobile robots: Kinematics analysis and control. *IEEE Transactions on Robotics*, *25*(1). https://doi.org/10.1109/TRO.2008.2010360

Ojeda, L., Cruz, D., Reina, G., & Borenstein, J. (2006). Current-based slippage detection and odometry correction for mobile robots and planetary rovers. *IEEE Transactions on Robotics*, *22*(2). https://doi.org/10.1109/TRO.2005.862480

Quann, M., Ojeda, L., Smith, W., Rizzo, D., Castanier, M., & Barton, K. (2017). An energy-efficient method for multi-robot reconnaissance in an unknown environment. *Proceedings of the American Control Conference*. https://doi.org/10.23919/ACC.2017.7963292

Quann, M., Ojeda, L., Smith, W., Rizzo, D., Castanier, M., & Barton, K. (2020a). Off-road ground robot path energy cost prediction through probabilistic spatial mapping. *Journal of Field Robotics*, *37*(3). https://doi.org/10.1002/rob.21927

Quann, M., Ojeda, L., Smith, W., Rizzo, D., Castanier, M., & Barton, K. (2020b). Power Prediction for Heterogeneous Ground Robots through Spatial Mapping and Sharing of Terrain Data. *IEEE Robotics and Automation Letters*, *5*(2). https://doi.org/10.1109/LRA.2020.2967717

Reina, G., Ojeda, L., Milella, A., & Borenstein, J. (2006). Wheel slippage and sinkage detection for planetary rovers. *IEEE/ASME Transactions on Mechatronics*, *11*(2). https://doi.org/10.1109/TMECH.2006.871095

Ward, C. C., & Iagnemma, K. (2008). A dynamic-model-based wheel slip detector for mobile robots on outdoor terrain. *IEEE Transactions on Robotics*, *24*(4). https://doi.org/10.1109/TRO.2008.924945