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Analysis and Comparison of Obstacle Avoidance Algorithms for Mobile Robots

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Abstract

Purpose of research. *Mobile robotics is a discipline of great interest today due to the wide range of applications for which it has potential for; ranging from industry, services, military, to space exploration. One of the most challenging aspects in the development of this technology is the implementation of accurate and efficient navigation and positioning systems, since this function will ensure the autonomous operation of this equipment, providing flexibility and reliability in the tasks to which these mechanisms are assigned to. In this research work, an analysis and comparison of the performance and behavior of 5 different algorithms of obstacles evasion was made, with the implements of the navigation system from a differential drive mobile robot (MR), from an initial point to a target point.*

Methods. *Routes for MR take place within a structured map with various obstacles in its environment. The MR is modeled using the inverse kinematics equations provided by the robotics. In order to guarantee the expected behavior of the algorithms, this project started from the primordial logic of each one. Therefore, the sequence that each algorithm follows was analyzed and encoded using the MatLab software, since its Simulink plug-in is very useful and versatile for test simulations. For the tests, 10 routes were defined within the structured map, which was called the "test map". To obtain the results, each algorithm was used to guide the mobile robot through each of the defined routes evaluating the distance and time used for each of them.*

Results. *For the analysis and comparison of the different simulated algorithms, an evaluation of the time and distance traveled was carried out to comply with 10 test routes with obstacles.*

Conclusion. *Algorithms can be classified into two classes: global planification (GP) and local planification (LP). GP is characterized by planning the route to be followed by the mobile robot prior to its movement, while LP plans in real time the route to be followed by the MR, a route which is calculated and recalculated iteratively based on the information from the environment outside the robot that is collected by the sensors.*

According to the results obtained, it can be concluded that LP algorithms have a superior performance to GP algorithms, so they are the most efficient for real applications. Although a correct combination of a GP algorithm with a LP could result in an optimal navigation system, which can overcome any type of obstacle and guide an MR efficiently through any type of environment no matter how complicated it is.

Keywords: *mobile robot; navigation system; algorithm; obstacle avoidance; navigation routes; kinematics.*

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Анализ и сравнение алгоритмов обхода препятствий мобильными роботами

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Abstract

***Цель исследования**. Мобильная робототехника сегодня вызывает большой интерес из-за широкого спектра приложений, для которых она может быть использована; начиная от промышленности, услуг, вооруженных сил и заканчивая исследованием космоса. Одним из наиболее сложных аспектов в развитии этой технологии является внедрение точных и эффективных систем навигации и позиционирования, поскольку эти функции делают возможной автономную работу робототехники, обеспечивая гибкость и надежность в задачах, для которых предназначены мобильные роботы. В данной работе был проведен анализ и сравнение производительности и поведения 5 различных алгоритмов обхода препятствий с помощью средств навигационной системы мобильного робота (МР), оснащенного дифференциальным приводом, от начальной точки до целевой точки маршрута.*

***Методы**. Маршруты для МР проходят по структурированной карте с различными препятствиями окружающей среды. МР моделируется с использованием уравнений обратной кинематики робота. Чтобы гарантировать ожидаемое поведение алгоритмов, данное исследование начиналось с изначального задания логики каждого из них. Поэтому последовательность действий, которой следует каждый алгоритм, была проанализирована и закодирована с помощью программного обеспечения MatLab, поскольку его подключаемый программный модуль Simulink универсален и подходит для данного тестового моделирования. Для тестов было определено 10 маршрутов в рамках структурированной карты, которая получила название «тестовая карта». Для получения результатов моделирования, каждый алгоритм использовался для направления движения мобильного робота по заданным маршрутам с оценкой расстояния и времени, затраченных на каждый из алгоритмов.*

Результаты. *Для анализа и сравнения различных смоделированных алгоритмов была проведена оценка времени и пройденного расстояния для 10 тестовых маршрутов с препятствиями.*

Заключение. *Алгоритмы можно разделить на два класса: глобальное планирование (ГП) и локальное планирование (ЛП). ГП выполняет планирование маршрута, по которому должен следовать мобильный робот, ещё до движения МР, в то время как ЛП в реальном времени выполняет построение маршрута, по которому должен следовать МР - данный маршрут рассчитывается и пересчитывается итеративно на основе информации, получаемой из внешней среды датчиками робота.*

По полученным результатам можно сделать вывод, что алгоритмы ЛП имеют превосходящую производительность по сравнению с производительностью алгоритмов ГП, поэтому они являются наиболее эффективными для реальных приложений. Хотя правильная комбинация алгоритма ГП с алгоритмом ЛП может привести к созданию оптимальной навигационной системы, которая может преодолевать препятствия любого типа и эффективно направлять МР в любой среде, независимо от того, насколько она сложна.

Ключевые слова: *мобильный робот; навигационная система; алгоритм; обход препятствий; навигационные маршруты; кинематика.*

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Introduction

The concept of a robot has different meanings, one of the most accepted ones is defined by the International Organization for Standardization (ISO). The ISO 8373 standard defines a robot as: “a reprogrammable multifunctional manipulator, capable of moving materials, parts, tools or special devices, through programmed variable movements, for the performance of various tasks” [1].

Being a complex device, there are several ways to classify automata, among the most important are:

1. According to the type of actuators: a. Pneumatic, b. Hydraulic and, c. Electric.

2. According to the type of control: a. Sequential, b. Trajectory-controlled, c. Adaptive, d. Tele-operated [2].

3. According to the application area: a. Personal or Domestic, b. Professional services (industrial), c. Research (I+D in robotics) [3].

4. According to the chronological development of the robots, it’s a classification by generations: a. First generation: they perform a repetition of the tasks for which they were scheduled in a sequential manner, b. Second generation: these are fitted with sensors that allow them to obtain information from its environment and act according to the current conditions of it, c. Third generation: these have a schedule and have the

ability to schedule their tasks according to the conditions of the work [1].

Mobile Robot (MR)

ISO 8373 defines a mobile robot as: "A robot that contains everything necessary for its piloting and movement (power, control and navigation system)" [2]. In general, an MR is composed of the following systems: a. Mechanical, b. Measurement and perception, c. Control, and d. Power supply. In Figure 1, the block diagram of a MR is presented [4].

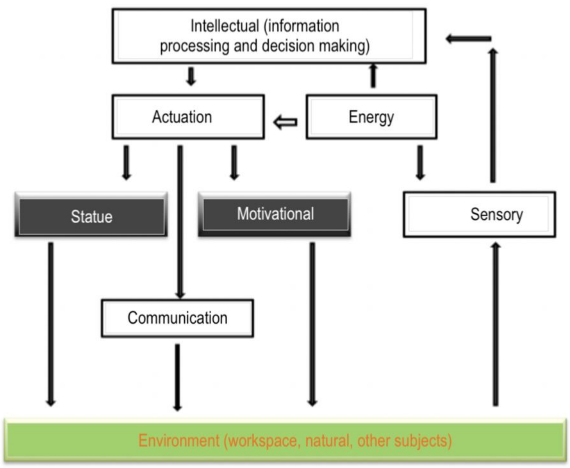


Fig.1. Block diagram of a MR

The mechanical system allows the MR to move according to the task for which it was designed. It is important to remember, that the purpose of an MR is not simply to move, for this automaton to be useful it must comply with a defined displacement that allows it to perform an assigned task.

According to the displacement mechanism, an MR can be classified into: a. Wheels, b. Legs and c. Tracks. Across various research works that have been carried out over time, it has been determined that the mechanism that offers the best performance are wheels, because they offer the following advantages: it has a better energy efficiency on smooth surfaces, causes less impact on travel surfaces, requires simpler systems with fewer components [5].

According to the kinematics required by the MR, three fundamental complications arise in terms of its design and operation: a. Location system, b. Navigation system and, c. The construction and recognition of maps of the work environment [6].

The localization function requires the MR to have a continuous knowledge of its position with respect to a frame of reference, this is a fundamental factor for the development of autonomous robots. In this way, devices can be distinguished according to their level of autonomy in the following categories: a. Guided devices, in which, the operation of the device is limited to predefined routes and, b. Unguided (autonomous) devices, which are not restricted to predefined routes [7].

Methods of localization

There is no single method of localization for MR, these can be focused on two groups: a. Relative position measurements and b. Absolute position. The relative position methods in turn are classified into: 1. Odometry and 2. Inertial navigation.

The absolute position measurement methods are classified into: 1. Magnetic positioners (compasses), 2. Active beacons, 3. Global positioning systems, 4. Navigation on reference points and correspondence models [8].

Odometry is one of the most reliable localization techniques for MR, it consists of integrating the information obtained through sensors of the displacement of the MR over time. It has as advantages: high levels of accuracy in small time intervals, high sampling rates and low cost. But also, by accumulating a large amount of information over time, it has the disadvantage that a large number of errors accumulate over time [9].These errors are of two types: systematic and no systematic, they depend on imperfections in the elements of the robot, as well as external causes such as sliding by the type of surface or any interaction of the robot with the contact surface. The measurement of errors in odometry is a critical process that can be very complex, Borenstein and Feng [10] developed a method of quantitative measurement of systematic errors for this localization technique that is widely used.

Navigation System

This is responsible for determining the most appropriate route to achieve the proposed objective, as well as avoiding the obstacles that may arise when traveling this route. This is a complex problem in the design of a mobile robot, since it can be found in environments with fixed objects or also areas where the dynamics are more complex since rapid changes in objects that represent obstacles for the automaton can occur.

For the implementation of the navigation control system it is advisable to divide the problem, so that it fulfills the following operations: 1. Establish the current position of both the automaton and the objects that are within the environment where the robot will be mobilized, 2. Avoid collisions with objects that are in front of the robot, 3. Determining the route that will be able to reach the target set for the robot and, 4. Resolve any conflicts that may arise for the fulfillment of the aforementioned tasks taking into account how the automaton kinematics are implemented.

Most of the methods developed for the solution of this problem, use techniques based on the use of computational intelligence and sophisticated control methods, which allow the robot to react quickly by adapting to the environment on which it must mobilize on.

According to the criteria of the navigation system of the mobile robot, these devices can be placed in two categories [11]:

a. Holonomic robot: these automata are able to modify their travel direction very quickly and without having to rotate beforehand. Therefore, they possess complete freedom of movement, because they are able to move in any direction at any time regardless of their orientation. That is why they are said to have the same degrees of freedom as of control.

b. Non-holonomic robot: these do not have the same movement capacity as the previous case and cannot be moved in all directions. This is why it is said that this type of robots have more degrees of freedom than control.

Navigation Methods

There are a wide variety of techniques that have been researched and developed for MR navigation, among the most important are [12]: a. Localization and cartography, b. Local and global navigation techniques, c. Arbitration by navigation commands and, d. Integrated approaches.

The Kalman filter (KF) is one of the most widely used methods for tracking and estimation due to its simplicity, optimality, tractability and robustness. Different implementations of the Kalman filter are presented in works [13-17]. This method is widely used in navigation systems of aircrafts, ships, submarines, spacecrafts, missiles, ground vehicles, etc. For a long time, this recurrent filter had a limited application due to the high requirements imposed on the onboard equipment of the robot in terms of computing capability and a large amount of memory required from the microcontrollers and other devices.

Obstacle avoidance algorithms

These work in the same way as any other algorithm would, counting on a general structure which will be repeated over and over again until the final goal is reached. They have the following elements:

Inputs: they use sensors (local planning), maps (global planning) and the final goal to be achieved by the mobile robot.

Process: it is composed of all the necessary operations and calculations by which it transmits the input information to reach the desired output. In the case of an obstacle avoidance algorithm, the process takes all the information from the sensors or from a preloaded map, and performs the route planning to reach the target.

Outputs: it is shaped by the desired angular direction in which the MR should move.

In this research work the following algorithms were analyzed [18]:

RRT (Rapid Random Tree): Uses randomness to define a feasible path between a starting point of the map to an end point in it. This randomness leads to the union of nodes along the map, chained one after the other, so that the structure that the algorithm forms resembles that of a tree and its branches.

RRT* (Rapid Random Tree Star): it is a modification of the RRT algorithm, among its variants there are: the addition of a ”neighborhood area or search area" that is formed to each node when it is generated. The second change is a record of the cost of each generated node, this cost refers to the distance traveled from the initial node to the new generated node. The last change allows the possibility of connecting an already existing node to the new generated node in a way that reduces the cost of the existing node.

PFPP (Potential Field Path Planning): in this a potential field of attraction is established around the objective to be reached, simultaneously a repulsive potential field is established around the obstacles to be avoided. In this way, attractive and repulsive forces are used to guide a mobile robot towards a specific target.

VFF (Virtual Force Field): Uses repulsive forces exerted by obstacles along with an individual attractive force exerted by the final target to guide the MR towards its goal, while dodging any obstacles that might arise on the way. This is a local planning algorithm, since it does not have any prior information about the map where the mobile robot will move and is only based on the information obtained by distance sensors placed around it, which verifies the obstacles in the vicinity of the robot.

VFH (Vector Field Histogram): it is a local planning algorithm, this can be considered as an evolution of the VFF algorithm. In the VFH, a larger number of sensors are used in order to cover all the surroundings of the MR and, due to the large number of sensors, the data received by these must go through a reduction and conditioning process before they can be used to calculate the direction in which the MR should move. This algorithm reduces the information of the robot's environment in a procedure divided into two steps. The first is the transformation of the Cartesian map where it shifts the MR into a 1D polar histogram (one dimension). The second step is the discretization of this histogram to proceed to divide the robot environment into sectors that can be considered as "busy" or free". After the determination of the state of all sectors, an evaluation is carried out to select the optimal direction, within one of the free sectors, in which the MR will be directed.

Methodology and tools

1. Modeling of the differential mobile robot.
2. Design of Models and Maps with obstacles.
3. Coding of Algorithms.
4. Simulations using MatLab and Simulink.

Modeling of the differential mobile robot

For this task, certain parameters of the robot were taken into account such as the angular and linear speed of the wheels, the radius of the same and the distance between the wheels of the robot. These parameters can be seen in Figures 2-3.

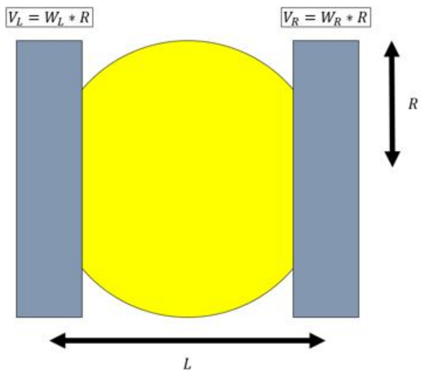


Fig. 2. MR parameters

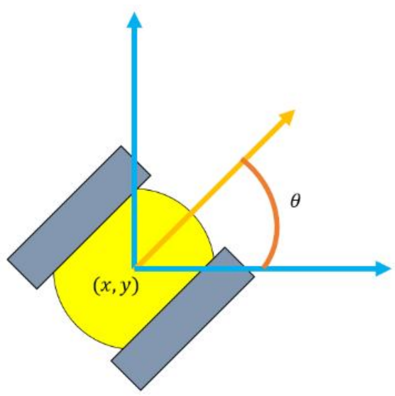


Fig. 3. Angular movement

The linear speed of the MR produced by the individual speeds of each wheel can be calculated by the following equation:

$$V = \frac{R \times W_R + R \times W_L}{2}, \quad (1)$$

and the angular velocity *W* of the robot can be calculated by the following equation:

$$\dot{\theta} = W = \frac{R}{L} \times \left(W_R - W_L\right), \quad (2)$$

where: V linear speed of the robot (m/s),

W – angular velocity of the robot (rad/s),

W_R – angular velocity of the robot right wheel (rad/s),

W_L – angular velocity of the robot left wheel (rad/s),

R – radius of the robot wheels (m),

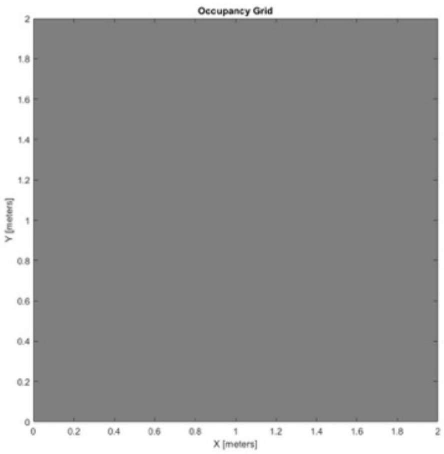
L – robot diameter (distance from wheel to wheel) (m).

Simplifying, an angular velocity W_L of the left wheel and an angular velocity W_R of the right wheel are expressed as the position variation of the robot on the X axis and Y axis, and the angular velocity as the variation of the angular position [19-21], thereof

$$\begin{cases} \dot{x} = \frac{R}{2} \times (W_R + W_L) \times \cos\theta \\ \dot{y} = \frac{R}{2} \times (W_R + W_L) \times \sin\theta \\ \dot{\theta} = \frac{R}{L} \times \left(W_R - W_L\right) \end{cases} \quad (3)$$

Test map modeling

This is done using the Matlab *occupancyMap* command, which is used to create a mesh of spaces of a certain width, height and resolution. Figure 4 shows a map of 20 spaces high x 20 spaces wide with a resolution of (1/10) meters per space, which generates a map of 2x2 meters. In order to define which spaces are empty and which are occupied, the *updateOccupancy* command is used. You can also see the map presented in the figure with the spaces (0.1, 0.1) and (2, 0.1) declared as occupied and empty spaces respectively.



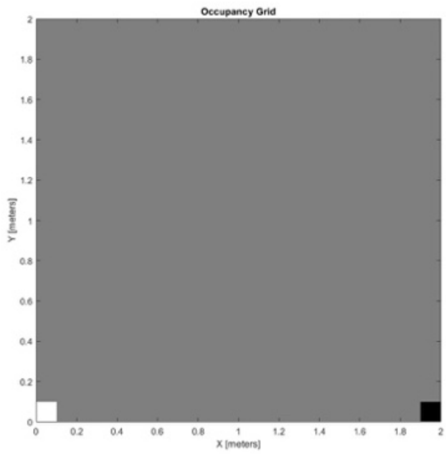


Fig. 4. A 2x2 meter map generated with occupancyMap and Map with updated occupancy values

For the simulation, two different maps are prepared. The first of these is the one that can be seen in Figure 5, which is a simple closed map of 2x2 meters with a square obstacle of 40 cm on each side that will be used to check the correct operation of the algorithms. In the figure on the right, you can see the second map, which is a closed map of 5x5 meters with several obstacles inside it that will be used to analyze the behavior of the algorithms after checking that they work correctly on the first map.

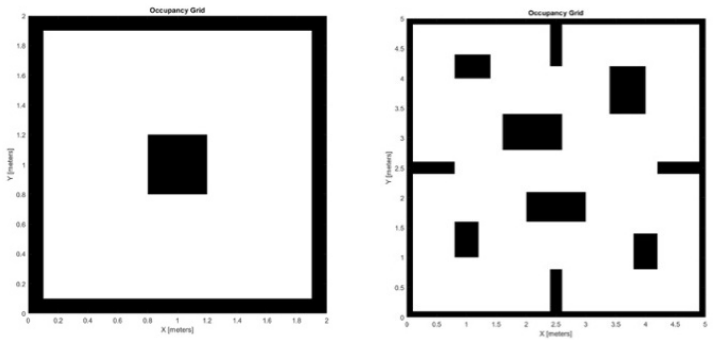


Fig. 5. Maps with obstacles for the verification of the algorithms

Results obtained

In Figure 6, the simulation of the route for each of the analyzed algorithms is presented.

For the analysis and comparison of the different simulated algorithms, an evaluation of the time and distance traveled was carried out to comply with 10 test routes with obstacles – Figures 7-8.

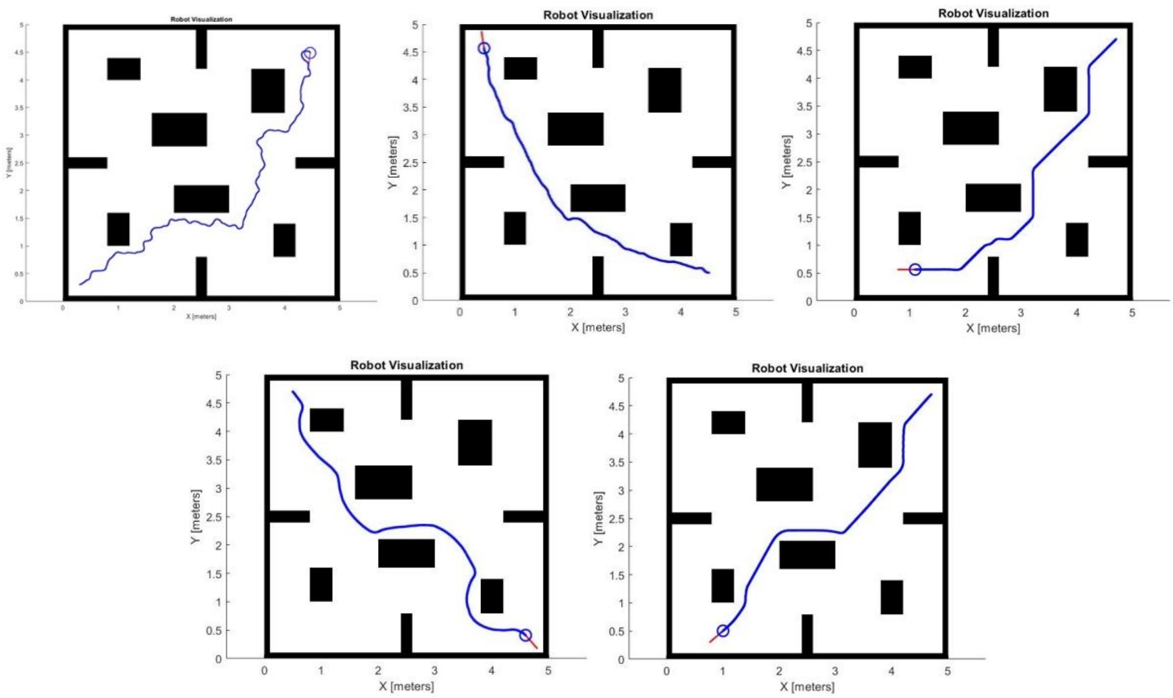


Fig. 6. Route simulation for RRT, RRT*, PFPP, VFF and VFH algorithms (from left to right)

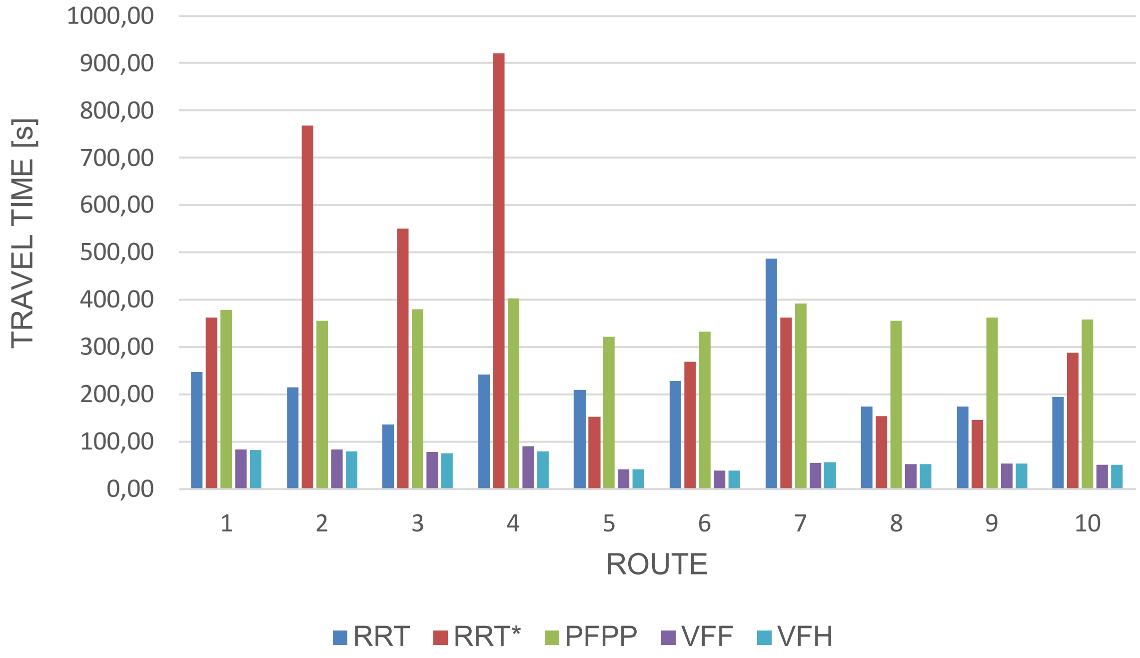


Fig. 7. Times for fulfillment of 10 routes of each algorithm

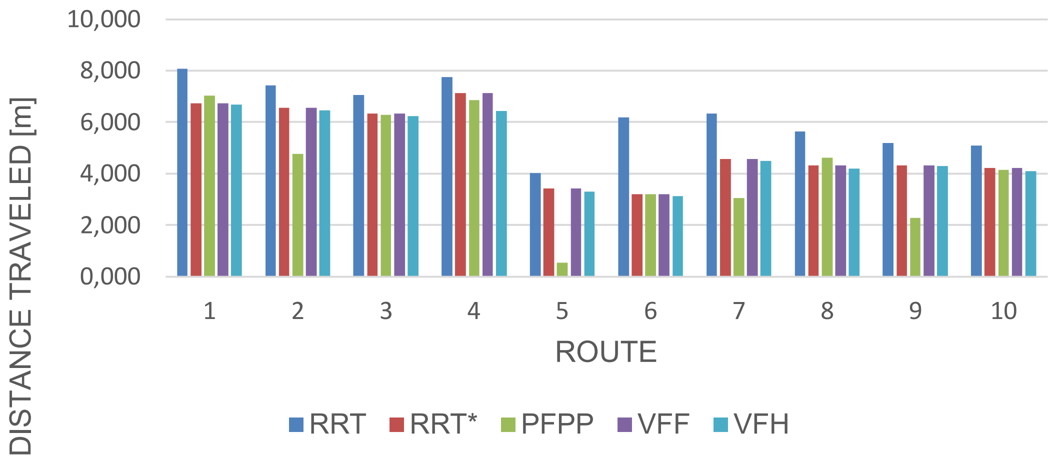


Fig. 8. Distances for compliance of 10 routes of each algorithm

Conclusions

Algorithms can be classified into two classes: global planification (RRT, RRT* and PFPP) and local planification (VFF and VFH). The global type (GP), are characterized by planning the route to be followed by the mobile robot prior to its movement, while the local type (LP) plans in real time the route to be followed by the MR, a route which is calculated and recalculated iteratively based on the information from the environment outside the robot that is collected by the sensors.

The GP algorithms reach the objective in a much longer time than the LP algorithms due to their analysis of the map, which, sometimes, can become excessive and inefficient.

LP algorithms have a great advantage, which is to plan the desired route to be followed by the MR in real time based on information from the surroundings of the MR, information that is measured by distance sensors. This quality gives a great potential to this type of algorithms, since they can be used for guide exploration MR, which could be used to map unknown and/or dangerous places.

LP algorithms travel a more efficient distance than GP algorithms. Another advantage to highlight is the time that these algorithms need to get from point A to point B, which is much reduced compared to GP algorithms, due to the fact that they do not need a previous route planning time.

The VFH algorithm, despite its complexity, it is the most effective and controlled algorithm. This generates optimal, short and stable routes, which guide the MR towards its goal in a relatively short time. However, the reaction of this algorithm to nearby frontal obstacles is slightly aggressive and could cause collisions in the case of having two obstacles very close to each other.

According to the results obtained, it can be concluded that LP algorithms have a superior performance to GP algorithms, so they are the most efficient for real applications. Although a correct combination of a GP algorithm with a LP could result in an optimal navigation system, which can overcome any type of obstacle and guide an MR efficiently through any type of environment no matter how complicated it is.

References

1. Barrientos A. *Fundamentos de Robotica.* McGraw-Hill. Second edition. 2007. 613 p.
2. UNE EN ISO 8373:1998. Robots manipuladores industriales. Vocabulario, 1998.
3. IFR. Clasificación de los robots de servicio por Áreas de aplicación según IFR / IFR. Available at: https://www.editores-srl.com.ar/sites/default/files/aa1_ifr_robots.pdf (Access date: 28.04.2020).
4. Chen X.Q., Chen Y.Q., Chase J.G. Chapter: Mobiles Robots – Past Present and Future. State of the Art in Land, Sea, Air, and Collaborative Missions. Libro. InterchOpen. 2009, 337 p.
5. Barrientos Sotelo V., García Sánchez J. R., Silva Ortigoza R. Robots Móviles: Evolución y Estado del Arte. *Revista Polibits*, 2007, vol. 35, no. 1, pp. 12-17.
6. Sorour M., Cherubini A., Khelloufi A., Passama R., Fraisse P. Complementary-route based ICR control for steerable wheeled mobile robots. *Robotics and Autonomous Systems*, 2019, no. 118, pp. 131–143.
7. Aguilera M. Diseño y Control de Robots Móviles. Instituto Tecnológico Nuevo Laredo, Aguilera M. Bautista M., Iruegas J. Available at: http://www.mecamex.net/anterior/cong02/papers/art24.pdf (Access date: 31.10.2022).

8. Borenstein J., Everett H. R., Feng L., Wehe D. Mobile Robot Positioning: Sensors and Techniques. *Journal of Robotic Systems*, 1997, no. 14, vol. 4, pp. 231–249.

9. Nakhaeinia D., Tang S. H., Mohd Noor S. B., Motlagh O. A review of control architectures for autonomous navigation of mobile robots. *International Journal of the Physical Sciences*, 2011, vol. 6(2), pp. 169-174.

10. Borensteinand J., Feng L. Measurement and correction of systematic odometry errors in mobile robots. *IEEE Transactions on Robotics and Automation,* 1996, vol. 6, no. 12, pp. 869–880.

11. Batlle J., Barjau A. Holonomy in mobile robots. *Robotics and Autonomous Systems*, 2009, vol. 57, pp. 433-440.

12. Ibrahim M. Y., Fernandes A. Study on mobile robot navigation techniques. *IEEE International Conference on Industrial Technology*, 2004, vol. 1, pp. 230-236.

13. Zhou B., Peng Y., Han J. UKF Based Estimation and Tracking Control of Nonholonomic Mobile Robots with Slipping. *Proceedings of the 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2008, pp. 2058-2063.

14. Bezmen P.A. *Digital filter for non-stationary signals*. Patent RF, no. 2747199, 2021 (In Russ.).

15. Bezmen P.A. *Control system based on the state of the control object with an observer and a state controller*. Patent RF, no. 2775514, 2022 (In Russ.).

16. Bezmen P. A. Investigation of the Operation of the Extended Kalman Filter Supplemented by an Adaptive Digital Filter for Integrating Data from a Mobile Robot Control System // *Izvestiya Yugo-Zapadnogo gosudarstvennogo universiteta = Proceedings of the Southwest State University*. 2020, 24(6): 68-89 (In Russ.). https://doi.org/10.21869/2223-1560-2020-24-1-68-89

17. Bezmen P.A. [Kompleksirovaniye dannykh sistemi upravleniya mobil'nym gusenichnym robotom]. *Bulletin of BSTU named after V.G. Shukhov*, 2022, no. 3, pp. 89–102. (In Russ.). DOI: 10.34031/2071-7318-2021-7-3-89-102.

18. Leca D., Cadenat V., Sentenac T. Sensor-based algorithm for collision-free avoidance of mobile robots in complex dynamic environments. *European Conference on Mobile Robot (ECMR).* Prague. Czech Republic, 2019, pp.1-6.

19. Juliano G. Iossaqui, Juan F. Camino, Douglas E. Zampieri A Nonlinear Control Design for Tracked Robots with Longitudinal Slip. *IFAC Proceedings Volumes*, 2011, vol. 44, is. 1, pp. 5932-5937.

20. Moosavian S. A. A., Kalantari A. Experimental slip estimation for exact kinematics modeling and control of a Tracked Mobile Robo. *IEEE/RSJ International Conference on Intelligent Robots and Systems,* 2008, pp. 95-100.

21. Martínez J.L., Mandow A., Morales J., Pedraza S., García-Cerezo A. Approximating Kinematics for Tracked Mobile Robots. *The International Journal of Robotics Research*, 2005, vol. 24, is. 10, pp. 867-878.

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