# Trajectory Tracking Nonlinear Control and Narrow Spaces Navigation of a WMR

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***Abstract*—In this paper is presented the movement control job of a wheeled mobile robot consisting in two tasks. The first task is to solve the nonlinear control for the trajectory tracking problem in presence of uncertainties. This task is solved using a new enhanced Sliding Mode Control law with a saturation component to reduce the chattering phenomenon and to force the reaching time of the sliding surface in presence of disturbances and uncertainties. The second task is to precise move the wheeled mobile robot movement through narrow spaces like doors. This task is accomplished using a proposed laser based narrow space driving algorithm. The real-time experiment of the movement control job is also presented.**

***Index Terms*—Sliding Mode Control, Wheeled Mobile Robot, Trajectory-tracking Control, Real-time Implementation**

## I. Introduction

Due to the evolution of the latest technology and research in the field of robotics, it has become possible to integrate robotic vehicles into the real world. From agriculture, mining, factories and hospitals, they increase safety, efficiency, productivity and performance in all tasks that are dirty or dangerous to humans.

Human like tasks are the main goal to be accomplished by autonomous robots. In order to achieve this desired aim, a lot of problems have to be solved. For example, a movement execution between a start point and a target point, in the working environment, has to be planned as a feasible path avoiding obstacles and, in the same time, has to consider some autonomy requirements criteria such as: safety, time and energy.

The most important and up to date achievements in the control and navigation of robotic systems aim at tracking a trajectory both indoor and outdoor. Theoretical and applicative results on nonlinear systems management through sliding-mode and back stepping techniques are recommended for a wide range of applications: controlling fast processes, robot manipulators and mobile robots.

In absence of the constraints generated by the requirements criteria, the free collision path determines the robot movement. The robot path model is a mathematical function with parameters to be determined as a solution of the path planning problem [1].

After solving the path planning problem, the resulted collision-free path, has to meet some other conditions. It has to be fast, safe, easy to use and to comply to some timed constraints generated either from the synchronization with another system or from the desired productivity rate of the system operating with the mobile robot. This is the trajectory tracking problem [2]. For the trajectory tracking problem, time duration to achieve the goal is the most important criterion. Sometimes, in the autonomous robot working space, there are narrow passages, like doors, compared to the robot size. To reach the target, the robot has to pass through this narrow passage. In order to accomplish this task, the robot has to use a laser sensor based Path Planning Algorithm [3].

In this paper, the Wheeled Mobile Robot (WMR) movement in a real environment, both indoor and outdoor, problem to be solved is defined like a two tasks job. Each task has a set of specifications to be considered. The two connected tasks are: 1) task one is the trajectory tracking problem for the robot movement from an initial point to a desired stop point; 2) task two is the robot movement through a narrow passage.

Task 1, the trajectory tracking problem for the robot movement from an initial point to a desired point, is solved using a nonlinear control sliding mode control (SMC). The sliding

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mode control has been widely used in recent years because of its robustness and simplicity [4], [5], [6]. The sliding-mode techniques have been analyzed and put into practice by many researchers [7], [8], [9]. The main advantages of the classical sliding mode are: robustness to external disturbances and uncertainties.

The widespread applications of SMC [10] is however restricted due to the relative degree of sliding variable and the chattering problem and generated different control laws for the SMC. In this paper, is presented a new SMC law with some advantages to be proved both in simulation and in the real time implementation.

Task 2, the passage through narrow spaces, compared to the size of the robot, is solved using a precise positioning movement algorithm and a new Path Planning Method. In the second section of this paper the first task of the robot moving job is presented. The trajectory tracking problem is solved using SMC. Section three is dedicated to the second task: the precise positioning movement through narrow spaces. The Path Planning Method, laser based, is presented. In the third section, the experimental results are presented.

Simulation and experimental results are performed using WMR PowerBot (2DW / 2FW) that has a maximum speed of 1.6 m/s and is able to carry a load up to 100kg.

## II. Nonlinear control of WMR

Classical sliding mode method has some limitations. One of these limitations is the presence of the chattering effect, due to high frequency switching control action. The main advantage of using the supertwisting sliding mode control is the reducing or elimination of the chartering effect and the maintaining of the robustness of the system. Moreover, the control scheme for the super-twisting sliding mode control approach is simpler and easier to implement in real time for the wheeled mobile robot. Super-twisting sliding mode control show improved performance in terms of decreasing oscillations and increasing robustness in presence of disturbance as shown in [11].

The problem to be solved in this paper is the control of the wheeled mobile robot to track a defined, plane trajectory in presence of the uncertainties. In the problem statement, it can be assumed that a virtual vehicle is moving on the desired reference trajectory and the real robot has to do the same motions as the virtual one as illustrated in Fig.1. The virtual vehicle position and orientation trajectories and also its kinematic equations are described in Equation 1:

$$\begin{bmatrix} \dot{x}_r \\ \dot{y}_r \\ \dot{\theta}_r \end{bmatrix} = \begin{bmatrix} cos\theta_r & 0 \\ sin\theta_r & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_r \\ \omega_r \end{bmatrix} \tag{1}$$

In Equation 2, the error dynamics for the position and angle for trajectory tracking are described:

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \tag{2}$$

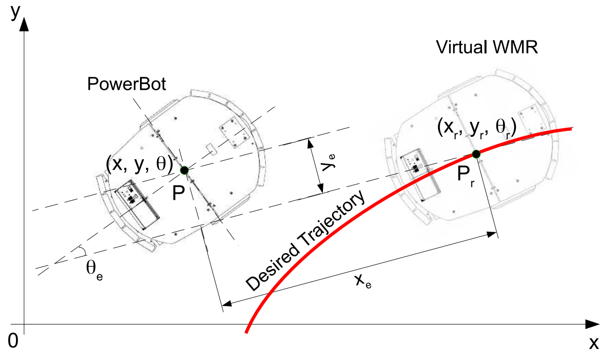


Fig. 1. The motion of real and virtual WMR

Consequently the errors dynamics gradient obtained after deriving the error dynamics for trajectory tracking are described in equation 3:

$$\begin{cases} \dot{x}_e = -v + v_r \cdot cos\theta_e + \omega \cdot y_e \\ \dot{y}_e = v_r \cdot sin\theta_e - \omega \cdot x_e \\ \dot{\theta}_e = \omega_r - \omega \end{cases} \tag{3}$$

In Fig.2 is presented the block diagram of the controlled system. The nonlinear controller is using a Sliding-Mode Control method to play the role of a dynamic tracking controller in order to ensure the convergence of the actual velocities of the real robot to the control velocities generated by the kinematic controller.

The following integral-type sliding surfaces are proposed:

$$\begin{aligned} s_1(t) &= x_e(t) + k_x \cdot \int_0^t x_e(\tau)d\tau \\ s_2(t) &= \theta_e(t) + k_\theta \cdot \int_0^t \left(\theta_e(\tau) + y_e(\tau) \cdot \frac{sin(\theta_e(\tau))}{\theta_e(\tau)}\right) d\tau \end{aligned} \tag{4}$$

where, the strictly positive real constants $k_e$ and $k_\theta$ have the role to determine the slope of the sliding surfaces. The two components of the control signal $u(t)$, based on SMC methodology, are described in Equation 5:

$$u(t) = u_{sm} + u_{eq} \tag{5}$$

The components of the equivalent control signal (the second component of the control signal) are described in the Equations 6:

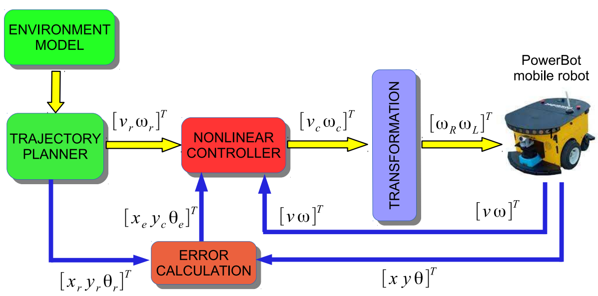


Fig. 2. Block diagram of the controlled system

$$
\begin{aligned}
u_{1eq} &= \omega \cdot y_e + v_r \cdot cos(\theta_e) + k_x \cdot x_e \\
u_{2eq} &= \omega_r + k_\theta \cdot \left(\theta_e + y_e \cdot \frac{sin(\theta_e)}{\theta_e}\right)
\end{aligned} \quad (6)
$$

The first component of the control signal, $u_{sm}$ in Equation 5, aims to force the state trajectory to reach the sliding surface in finite time in presence of the disturbances and model uncertainties in the system. The reaching law for this purpose is chosen as:

$$
u_{ism} = -Q_i \cdot s_i - P_i \cdot sign(s_i), i = 1, 2 \quad (7)
$$

where, the positive constants $Q_i$ and $P_i$ are the switching gains in the general SMC control law. The $Q$ and $P$ constants have to be chosen in order to compensate the system uncertainties and disturbances. Equation 8 calculates the total control law of the system:

$$
\begin{aligned}
u_1 &= -Q_1 \cdot s_1 - P_1 \cdot sign(s_1) + \omega \cdot y_e + \\
&+ v_r \cdot cos(\theta_e) + k_x \cdot x_e \\
u_2 &= -Q_2 \cdot s_2 - P_2 \cdot sign(s_2) + \omega_r + \\
&+ k_\theta \cdot \left(\theta_e + y_e \cdot \frac{sin(\theta_e)}{\theta_e}\right)
\end{aligned} \quad (8)
$$

One can see that when $\theta_e \to 0$ then $\frac{sin(\theta_e)}{\theta_e} \to 1$.

The $sign$ function is replaced by a $saturation$ function, in order to reduce chattering. The components of this function are described in Equation 9, and they are calculated because the switching control unwanted effect is that it usually causes chattering in the state trajectory on the switching surface.

$$
sat(s_i) = \begin{cases} 1 & if \quad s_i/\varepsilon > 1 \\ s_i/\varepsilon & if \quad -1 < s_i/\varepsilon > 1 \\ -1 & if \quad s_i/\varepsilon < -1 \end{cases} \quad (9)
$$

where $\varepsilon$ is the constant indicating thickness of the boundary layer.

The real time implementation of this new enhanced control law is presented in section IV.

## III. Narrow Space Driving Algorithm

A driving system for a mobile robot that can pass through a door has become a very important objective for autonomous vehicle navigation because when combined with the wall tracking system or the corridor tracking system it creates a complete navigation system in the case of interior environments [12].

The narrow space driving algorithm is based on an algorithm that uses the information from the laser sensor. It is designed to detect any path/way out of a room, taking into account the real dimensions of the mobile robot. The real dimension of the mobile robot is transposed into the size of the angle window.

In this work, the dimension of the angle window is constant. This size ensures that the number of angles (points) of the laser involved in the frontier point detection will cover a neighbourhood equal to the width of the mobile robot (in this paper PowerBot robot) plus 10% in order that the robot not to remain stocked in any narrow space.

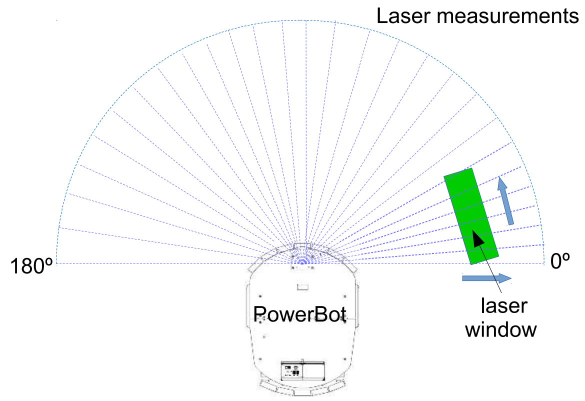


Fig. 3. Laser sensor windows scanning

When the range of the laser measurement is close to the mobile robot, the window covers a higher number of degrees than when the range is longer (as is easy to observe in Fig. 3). From a range of 0.5 m the mobile robot searches for possible nodes with a minimum distance between them. In this work, minimum distance equal with 0.2 m was adopted. Also, the representing frontier point from a set of consecutive frontier points will be the mean point, as it is shown in Fig. 4.

Figure 4 shows an example situation of the path planning using angle windowing procedure. The path generation is a dynamic procedure. This is determined by the fact that every time when the mobile robot reaches a point, the path is updated with the next median point of the narrow space it has to pass through.

Case 1 - the mobile robot is positioned in front of an open door, and following the chart obtained with Matlab, it can be seen that the trajectory it sets itself, according to the requirements of the proposed algorithm, is the passage of the front space represented by the opening of the door, Fig. 5.

Case 2 - the mobile robot is far away from the open door, but at a distance closer to the left wall, it decides to follow the path described in Fig. 6.

Case 3 - the mobile robot is placed in the corridor, but this time the nearby door is closed, so the only empty space detected is represented by the corridor, 7.

The proposed algorithm (presented in I) allows wheeled

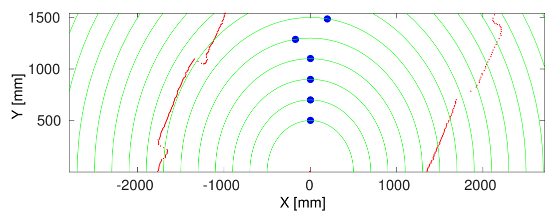


Fig. 4. Detection of median points

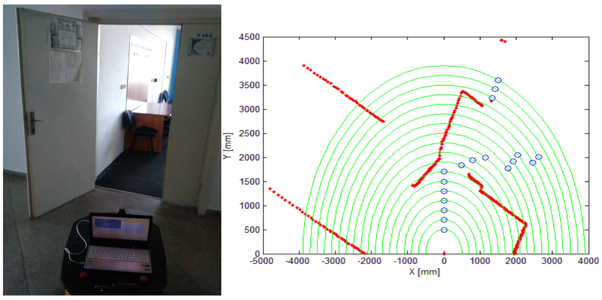


Fig. 5. Real mobile robot in front of an open door and path produced

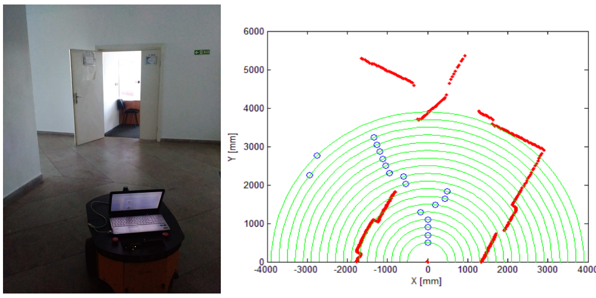


Fig. 6. Real mobile robot far away from the open door and the path produced

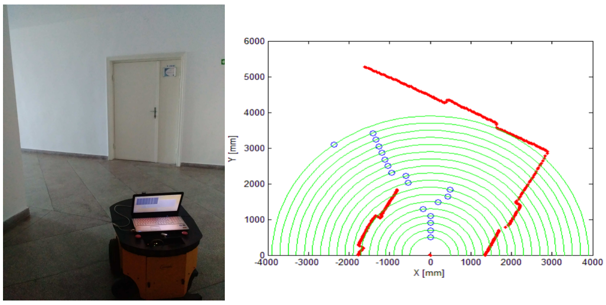


Fig. 7. Real mobile robot placed in the corridor with the nearby door closed and the path produced

mobile robots to move through narrow spaces, such as a door or narrow rooms. This is done using a laser sensor (Hokuyo type) that can detect a free path through obstacles. This determines the middle (middle) point of the free windows to be used in the mobile robots algorithm.

TABLE I
PSEUDOCODE OF NARROW SPACE DRIVING ALGORITHM

```
for arc dimension = 0.5:0.2:4
        for each window
                for each points inside the window
                        if arc dimension < laser point
                        then P = mean
                        else P = 0
                        end
                end
                Pw = mean of P
        end
        Pfinal = [Pfinal Pw]
end
```

The route to be traversed by the mobile robot is composed of the median points calculated according to the number of free windows. The algorithm runs in real time. After moving the first median set of points, other set of median points will be recalculated (as an effect of updating the position of the mobile robot).

## IV. Real time implementation

The present work has two objectives transformed in interest points.

The first one considers the WMR PowerBot as a transportation resource in a flexible manufacturing system. This system is a flexible manufacturing line for processing /reprocessing and the WMR has to transfer the pieces that did not pass the quality check, from the quality check station to the buffer. This means that the robot take the defect piece, passes along the assembly/disassembly mechatronics line, and has to pass through a rather complicated route because this is done within the facultys laboratory which is narrow and obstructed. The buffer where the defect piece has to be stored makes the WMR to leave the room through the door.

This is the second interest point of the experiment presented in this paper. Due to its large dimensions, it must pass through the door with perfect precision. This task is possible because of the use of the laser sensor.

The proposed controller is tested on the PowerBot mobile robot (see Fig. 8). PowerBot is a high-payload differential drive robotic platform. This platform is an automated guided vehicle, specially designed and equipped for autonomous, intelligent delivery and handling of large payloads.

There are some constraints for the real time implementation. The algorithm considers the sensor information in the maximum range of 4 meters because it works on-line and this 4 meters zone is enough for the mobile robot to observe the walls of the narrow passage walls because next step (e.g. after maximum 4 points x 100 ms) a new prediction for the median points is made.

The real-time experiment is presented in Fig. 9. The proposed controller can track the trajectory with minimum errors.

Figures 10 to 12 show graphically the experimental results on the PowerBot mobile robot.

In Fig. 10, it is observed how the posture tracking and orientational errors tend to zero and stay there for the remainder of the experiment.

The control speeds generated by the nonlinear controller have smooth control signals, as illustrated in Figs. 11 and 12. With respect to the velocities of mobile robot, it can be observed that these speed track the command speed.

## V. Conclusions

Once the control system has been evaluated and the simulations have proved to be satisfactory, a real scenario is used to validate the proposed nonlinear controller. The validation results of the complete WMR behaviour through a real-time scenario are presented. The real-time test consists in starting from an initial point (position), following the desired trajectory


Fig. 8. The PowerBot mobile platform used in the real experimental scenario

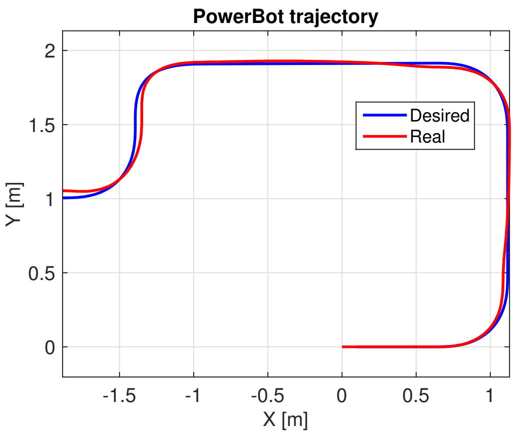


Fig. 9. Trajectory tracking in the real experimental scenario

and finally stopping in front of a door. The scenario where the test has been performed is a geometrically circuit.

The main contribution of the paper is the proposal of the new sliding surface for the nonlinear controller. The second contribuition is the proposed laser based narrow space driving algorithm. Experiments whith a real robot system have been conducted and the result confirmed the effectiveness of the proposed methods.

In the future we intent to compare the proposed nonlinear controller with some other existing nonlinear controller approaches.

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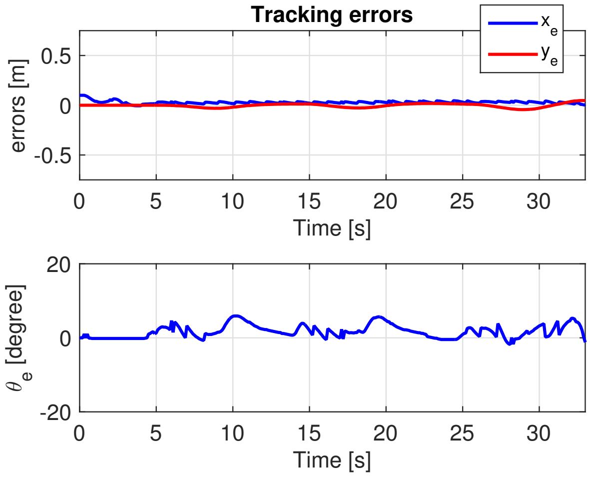


Fig. 10. Posture tracking and orientational errors in the real experimental scenario

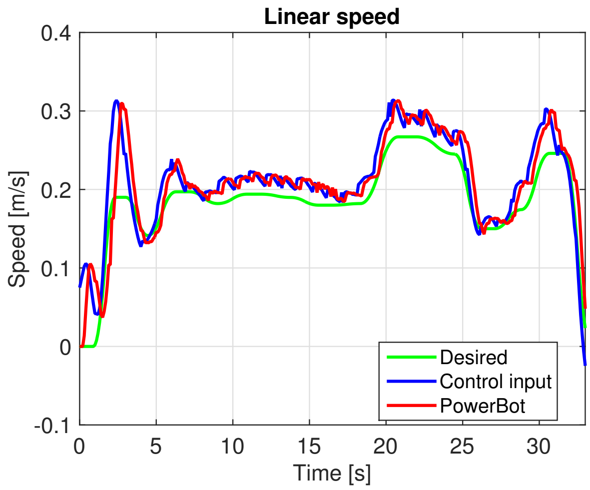


Fig. 11. Control and real linear speeds in the experimental scenario

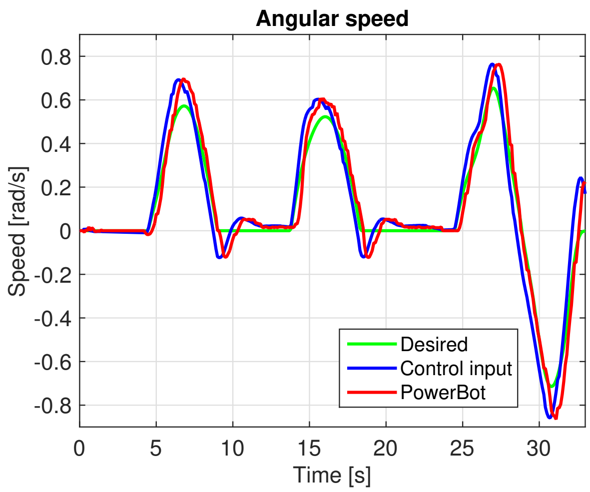


Fig. 12. Control and real angular speeds in the experimental scenario

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