Neural Model in Mobile Robot Trajectory Following Task

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***Abstract* — this article is devoted to the problem of reference trajectory tracking by the mobile robot with differential wheeled chassis and comparison of classical and intelligent control methods used for this task. The article presents the advantages of an intelligent approach in the control of mobile robot compared to classical control method. The obtained mathematical model of a mobile robot is implemented as simulation model in Simulink with an internal control loop for wheel velocities and then used in classical control structure for tracking the reference trajectory based on feedforward and feedback control. The intelligent control uses trained inverse neural model as the feedforward control part. Neural model is created and trained using application library Neural Network Toolbox. Article is enclosed by comparison of classical and intelligent control performance for selected type of the reference trajectory.**

***Keywords* — mobile robot, feed-forward neural network MLP, reference trajectory tracking, inverse neural model, Neural Network Toolbox**

I. INTRODUCTION

Modeling and control of mobile robots are nowadays subjects of interest in several papers, e.g.: [1] and [2]. Since the neural networks have property to approximate nonlinear functions, we can use them in the task of the reference trajectory tracking by mobile robot. This way we can create and use an intelligent control structures that can perform better than the classical methods in certain tasks. In this article, that is also an output of Diploma thesis [7], we focus on intelligent control structure of mobile robot that uses inverse neural model for the reference trajectory tracking. The neural model will be obtained using application library Neural Network Toolbox in Matlab environment and the experiments will be conducted in simulation language Matlab/Simulink.

II. INTELLIGENT CONTROL STRUCTURE FOR MOBILE ROBOT REFERENCE TRAJECTORY TRACKING

The reasons why we are using these intelligent methods are: prediction ability of trained neural model, possible better control quality and tolerance to uncertainty in training data. Moreover, this approach has additional options such as online training, possibility to combine with fuzzy control, genetic algorithms and similar features. The neural model, that is used in intelligent control structure for reference trajectory tracking is trained to specific type of trajectory. In control structure (Fig. 5) we replace feedforward control part by an inverse neural model of mobile robot. Resulting block diagram of the intelligent control structure is depicted on Fig. 1.

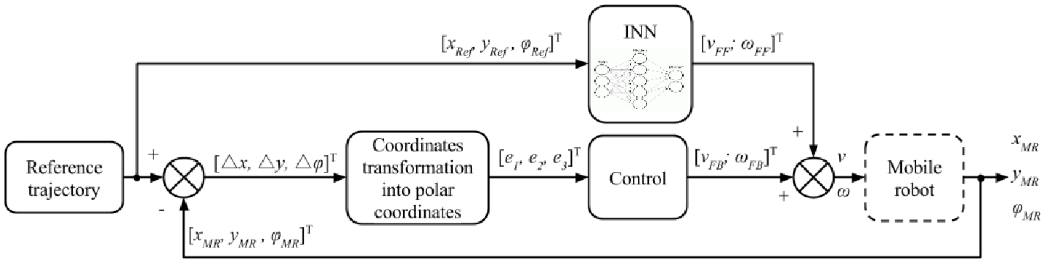


Fig. 1 Control structure for reference trajectory tracking that use inverse neural model as feedforward control part

Block diagram depicted on Fig. 2 shows the input vectors that are used in training and testing of inverse neural model used in control structure. The outputs of this model are the desired forward linear velocity v_{FF} and angular velocity ω_{FF} of the mobile robot.

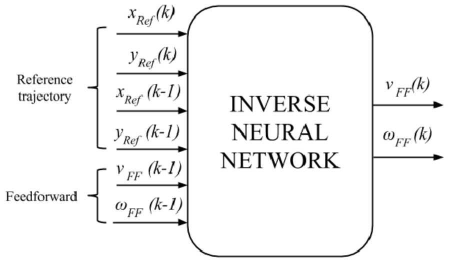
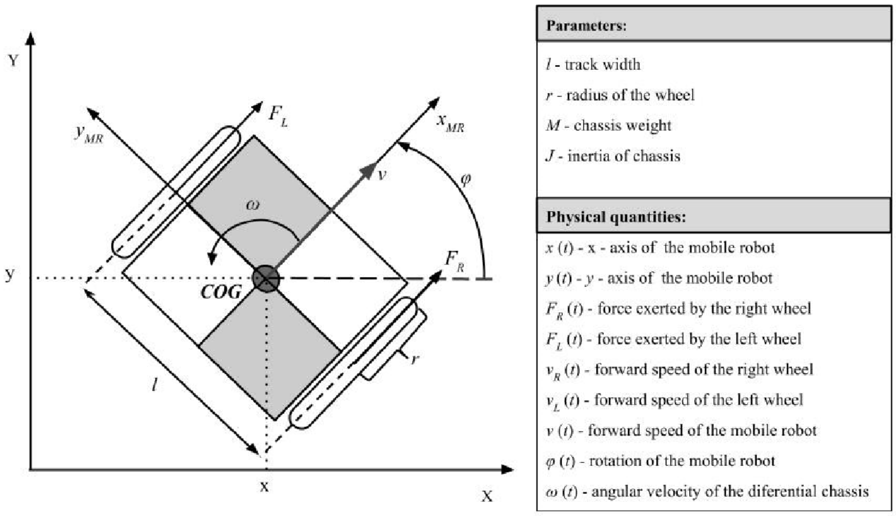


Fig. 2 Block diagram of the inverse neural model

III. MATHEMATICAL MODEL OF MOBILE ROBOT AND ITS PROPERTIES

Basic scheme of mobile robot with the description of parameters and dimensions is shown on Fig. 3. The mathematical model of mobile robot can be divided into two main parts - the kinematic model and the dynamic model.



Parameters:

l - track width
r - radius of the wheel
M - chassis weight
J - inertia of chassis

Physical quantities:

$x(t)$ - x - axis of the mobile robot
$y(t)$ - y - axis of the mobile robot
$F_R(t)$ - force exerted by the right wheel
$F_L(t)$ - force exerted by the left wheel
$v_R(t)$ - forward speed of the right wheel
$v_L(t)$ - forward speed of the left wheel
$v(t)$ - forward speed of the mobile robot
$\varphi(t)$ - rotation of the mobile robot
$\omega(t)$ - angular velocity of the diferential chassis

Fig. 3 Principal scheme of mobile robot with description of parameters

A. *Kinematic model of mobile robot for odmometry*

The kinematic model can be obtained as the center of gravity (COG) movement description in the plane defined by its coordinates x, y and rotational angle φ. Vector for robot's forward speed consist of two components, the speed in the X axis v_x and speed in the Y axis v_y. This type of the kinematic model is often called as "unicycle" and is defined according to [1] as follows:

$$\begin{aligned} v_x &= v\cdot\cos\varphi \\ v_y &= v\cdot\sin\varphi \\ \dot{\varphi} &= \omega \end{aligned} \quad \rightarrow \quad \begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\varphi}\end{bmatrix} = \begin{bmatrix} cos\,\varphi & 0\\ sin\,\varphi & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix} v\\ \omega\end{bmatrix}. \tag{1}$$

Because of control demands, we use velocity relations

$$\begin{aligned} v_R &= v + \frac{l}{2}\omega & \qquad v_R &= r\omega_R, \\ v_L &= v - \frac{l}{2}\omega & \qquad v_L &= r\omega_L, \end{aligned} \tag{2}$$

to obtain kinematic model defined for wheel angular velocities ω_R and ω_L.

B. *The dynamic model of mobile robot defined for forces generated by engines*

According to [2], using the 2. Newton's law (force law), the forward acceleration of the mobile robot v can be expressed by forces F_R and F_L generated by robot wheel engines as

$$M\ddot{v} = F_R + F_L. \tag{3}$$

Analogically, the same law applies for the robot overall angular acceleration as

$$J\ddot{\omega} = F_R\frac{l}{2} - F_L\frac{l}{2}. \tag{4}$$

C. *Internal control loop*

To suppress the dynamics of the mobile robot, an internal control loop need to be used. The control task is to minimize the difference between desired and actual wheel velocity. The simple controller for right wheel with limits is defined as

$$\begin{aligned} F_R &= k(\omega_{Ref} - \omega_R) && \text{for } \left|k(\omega_{Ref} - \omega_R)\right| < F_{max} \\ F_R &= F_{max} \cdot sign(\omega_{Ref} - \omega_R) && \text{for } \left|k(\omega_{Ref} - \omega_R)\right| \geq F_{max} \end{aligned} \tag{5}$$

where F_{max} is the maximum traction force produced by wheel engine. Analogically, the same controller applies for left wheel. The control stability condition requires positive definition of the k constant [3].

D. *The simulation model of mobile robot with an internal control loop*

The simulation model of mobile robot that consists of kinematic model and dynamic model with internal control loop is depicted on Fig. 4 and hereinafter referred as mobile robot block in control structures. The inputs are wheel angular velocities and the output is its position in plane.

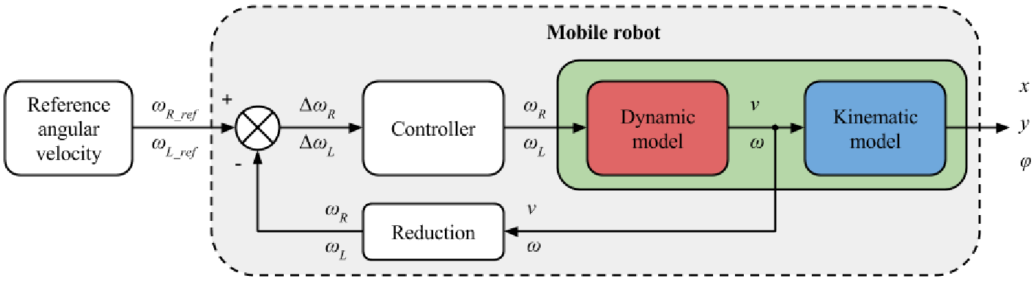


Fig. 4 Block diagram of the mobile robot with internal control loop

IV. FEEDFORWARD AND FEEDBACK CONTROL STRUCTURE FOR MOBILE ROBOT REFERENCE TRAJECTORY TRACKING

The control structure later used in simulation experiments is based on control law that consists of feedforward and feedback part. The feedforward and feedback control law parts along with mobile robot model mentioned above is depicted on Fig. 5 as control structure for reference trajectory tracking.

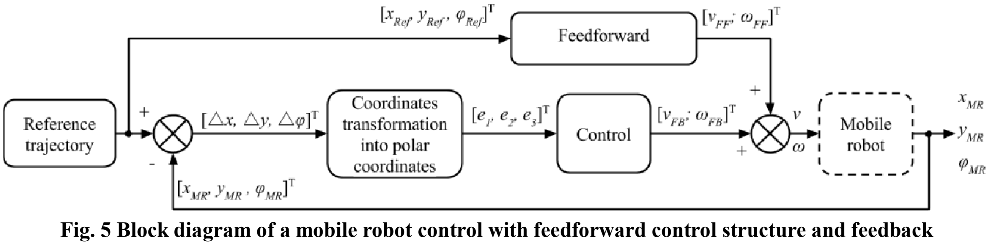


Fig. 5 Block diagram of a mobile robot control with feedforward control structure and feedback

As mentioned previously, this structure is later enhanced by neural model as shown on Fig. 1. Definition of feedforward and feedback control parts is according to [4] a sum

$$\begin{aligned} v &= v_{FF} + v_{FB} \\ \omega &= \omega_{FF} + \omega_{FB} \end{aligned} \tag{6}$$

where v_{FF}, ω_{FF} are the feedforward and v_{FB}, ω_{FB} are the feedback components of control law.

The feedforward part of the control is the mobile robot reference linear velocity v_{FF} calculated from trajectory reference position coordinates x_{Ref} and y_{Ref} as

$$v_{FF} = \pm\sqrt{\dot{x}_{Ref}^2 + \dot{y}_{Ref}^2}. \tag{7}$$

where ± means direction. The desired rotation angle for the mobile robot can be obtained as

$$\varphi_{FF} = \operatorname{atan2}(\dot{y}_{Ref}, \dot{x}_{Ref}). \tag{8}$$

By derivation of (8) we get the reference angular ω_{FF} velocity given by

$$\omega_{FF} = \frac{\dot{x}_{Ref}\ddot{y}_{Ref} - \dot{y}_{Ref}\ddot{x}_{Ref}}{\dot{x}_{Ref}^2 + \dot{y}_{Ref}^2} \tag{9}$$

The equations (7) and (9) represent the feedforward control part in (6).
To get the feedback control part, it is necessary to define error variables. The difference between the reference $\left[x_{Ref}\ y_{Ref}\ \varphi_{Ref}\right]$ and current robot posture $[x_{MR}\ y_{MR}\ \varphi_{MR}]$ can be described as an error posture defined using the rotation transformation matrix in mobile robot local coordinate system like in [4]. The position and angle errors can be summed in matrix from as and the error posture is depicted on Fig. 6 .

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\varphi_{MR} & \sin\varphi_{MR} & 0 \\ -\sin\varphi_{MR} & \cos\varphi_{MR} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{Ref} - x_{MR} \\ y_{Ref} - y_{MR} \\ \varphi_{Ref} - \varphi_{MR} \end{bmatrix} \tag{10}$$

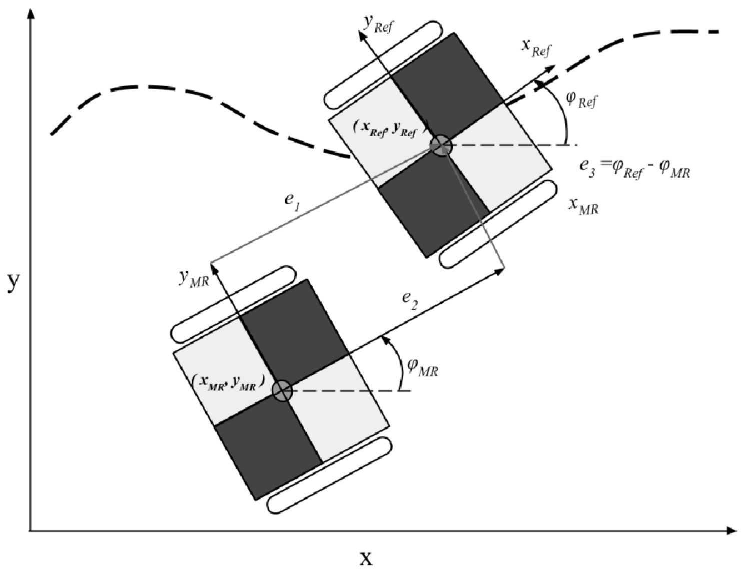


Fig. 6 Definition on posture erros between current and reference mobile robot position

The feedback control that ensures stability is defined as

$$\begin{bmatrix} v_{FB} \\ \omega_{FB} \end{bmatrix} = \underbrace{\begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & k_3 \end{bmatrix}}_{\boldsymbol{K}} \cdot \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}. \tag{11}$$

where the gains in matrix $\boldsymbol{K}$ defined as k_1 k_2 and k_3 must ensure that the eigenvalues of the system will be located on the left side of the complex plane. The equation (11) represents the feedback control part in (6).

V. APPLICATION OF INVERSE NEURAL MODEL IN CONTROL STRUCTURE

The first task before creation and application of the neural model in control structure is to implement simulation scheme that enables data collection in closed loop experiment [5], the Simulink scheme is shown on Fig. 7.

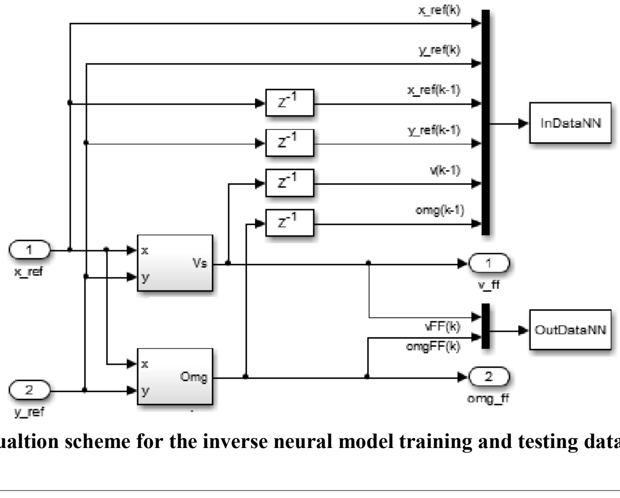


Fig. 7 Simualtion scheme for the inverse neural model training and testing data acquisiton

The obtained data set contains the feedforward linear and angular velocities in reasonable length which is later divided into training data (75%) and testing data (25%). The chosen reference trajectory is shown on Fig. 8.

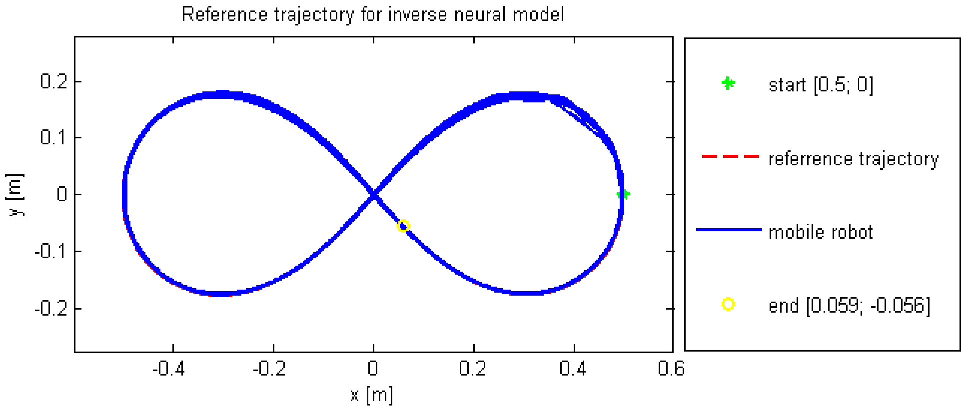


Fig. 8 Reference trajectory for the inverse neural model

Training, testing and creation of inverse neural model is performed under application library Neural Network Toolbox, more details about procedure can be found in [6]. The neural model is based on feedforward MLP. We have chosen Gauss-Newton optimization method, which minimize the criterion for training of the inverse neural model:

$$J = \frac{1}{2N}\sum_{i=1}^{n}(y(i) - \hat{y}(i))^2. \qquad (12)$$

The number of neurons in the hidden layer is equal to the number of inverse neural model input vectors. The resulting neural model is generated as a functional block in Matlab/Simulink, which is then inserted into control structure on Fig. 5 as feedforward control part and this substitution produces an intelligent control structure presented on Fig. 1. Validation of the inverse neural model for the reference trajectory tracking task is performed by scheme depicted on Fig. 9.

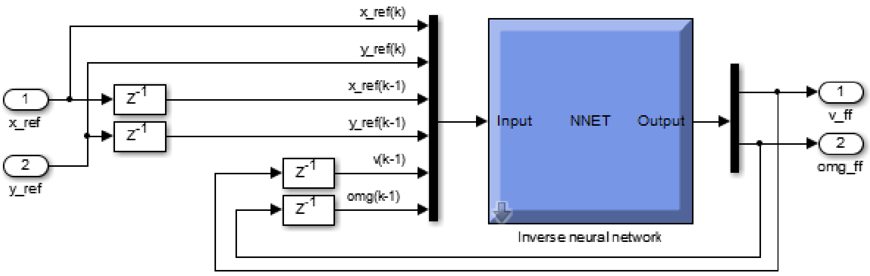


Fig. 9 The application of inverse neural model in feedforward control part of contol structure

VI. COMPARISON EXPERIMENTS BETWEEN THE CLASSIC AND INTELLIGENT APPROACH IN MOBILE ROBOT REFERENCE TRAJECTORY TRACKING TASK

The final comparison experiment shown on Fig. 10 illustrates the performances of classical and intelligent control approach. In both experiments, the mobile robots have the same starting point and reference trajectory. The time of experiments is 6.24 s with 0.01 s sample rate.

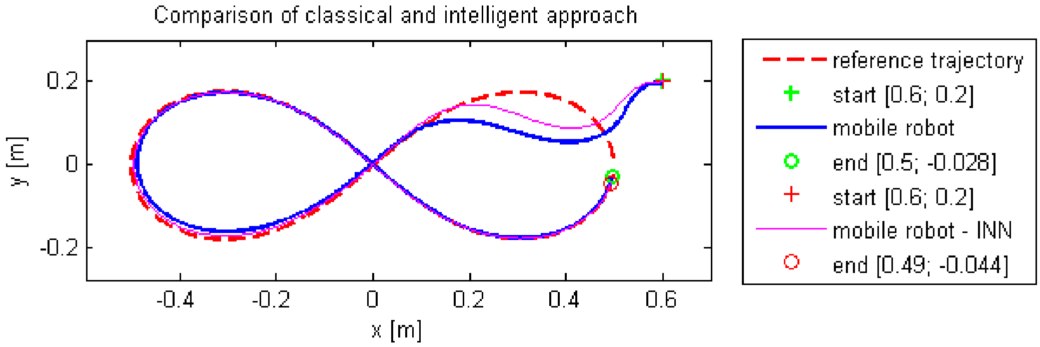


Fig. 10 Comparison of classical and intelligent control strucutures

The posture errors converge in both approaches, as shown on Fig. 11. The $\boldsymbol{e_1}$ rate of convergence is better in classical approach, however, the convergence of $\boldsymbol{e_3}$ is better in intelligent control approach.

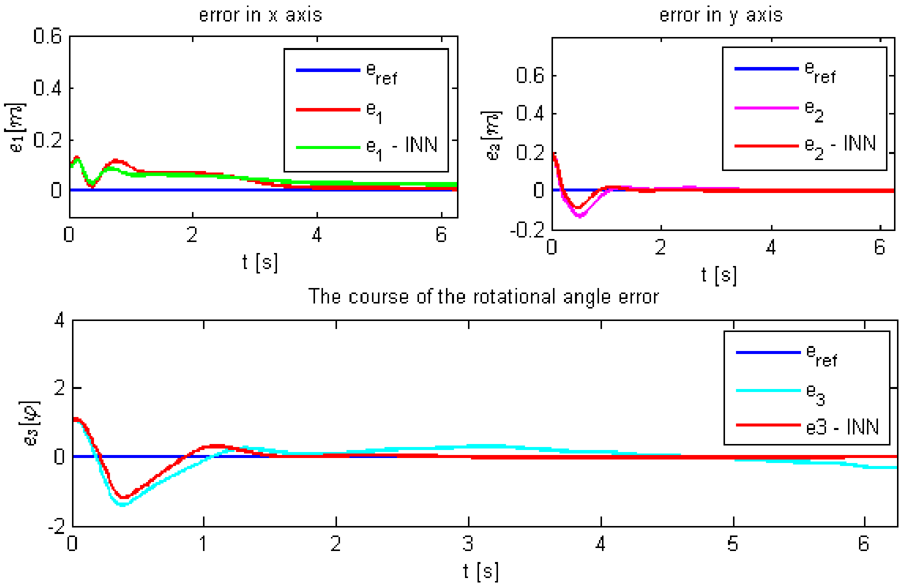


Fig. 11 Coparison of errors e_1, e_2 and e_3 from classical and intelligent method control of the mobile robot in reference trajectory tracking

VII. CONCLUSION

This article presents the simulation experiment of classical and intelligent approach in mobile robot reference trajectory tracking task. Mathematical model of mobile robot, which consists of kinematic and dynamic models with internal control loop, has been verified in the closed loop control structure. Obtained data were used to train an inverse neural model to specific trajectory and this model substituted the feedforward part in classical control structure to get an intelligent control structure. From the results of comparison experiments, we can conclude that the mobile robot in intelligent control structure can track the reference trajectory as good as in classical approach, even better in some ways.

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