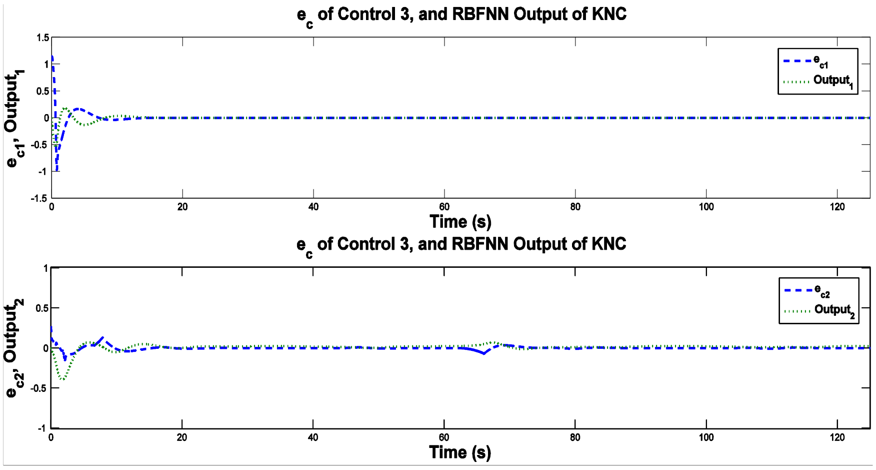

Figure 33. Auxiliary velocity tracking errors of Control 3 and RBFNN outputs ($\hat{P}_v(\sigma^*)$, (52) of the KNC controller with the neural term

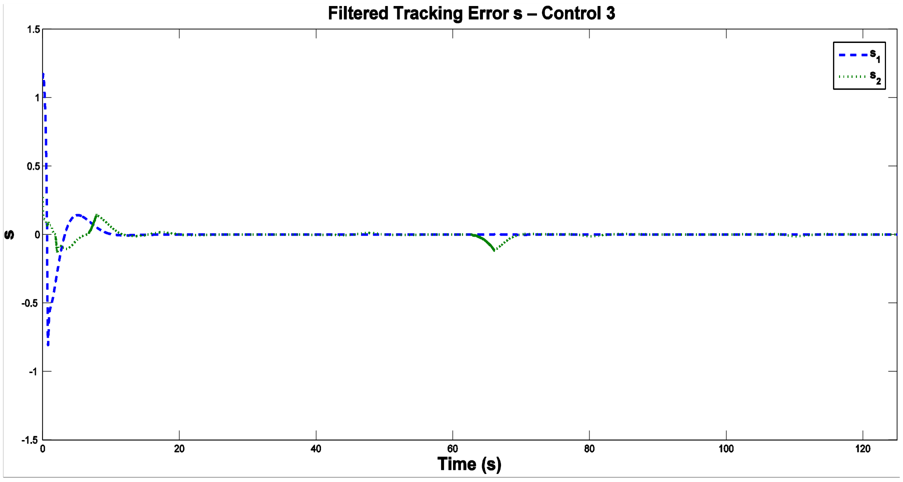

Figure 34. Filtered tracking errors using the KNC controller with the neural term

It should be noted that for the Controls 1, 2 and 3, the sliding surfaces (Fig. 35) and new sliding surfaces (Fig. 37) converge to zero, and the chattering is eliminated. Additionally, for Control 2, the filtered tracking errors (Fig. 34) converge to zero, and the chattering is eliminated.

The comments made in Subsection 4.2 are also valid in this subsection, both

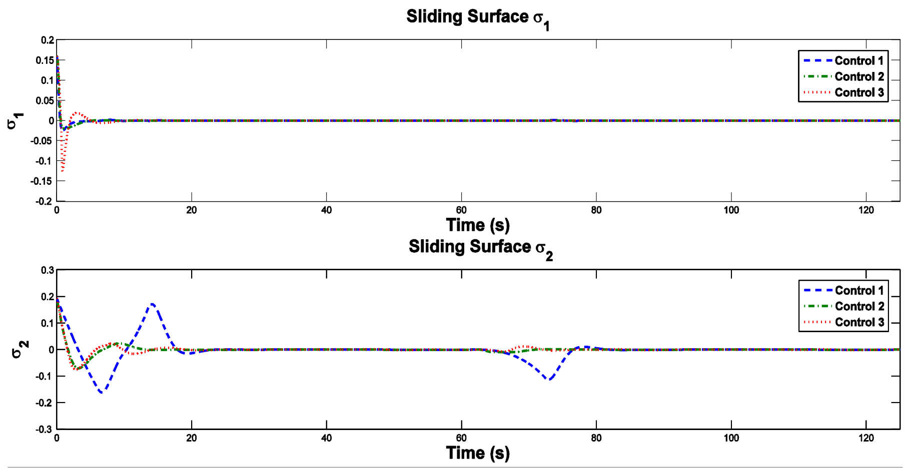

Figure 35. Sliding surfaces using the KNC controller with the neural term

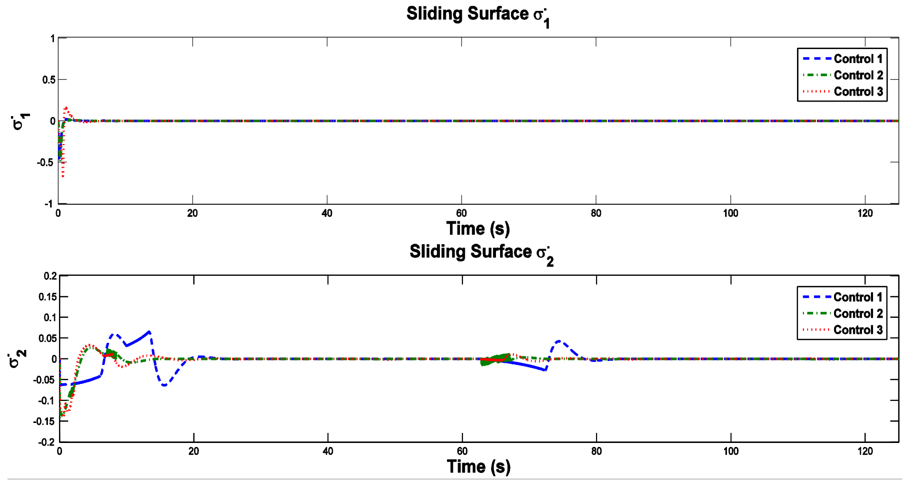

Figure 36. Derivatives of sliding surfaces using the KNC controller with the neural term

for the RBFNN outputs of the robustness term γ_s of the TNC controller of Control 3 under the influence of disturbances to the wheeled mobile robot (Fig. 39), and for the estimation of parameters of the inertia matrix $\bar{H}(q)$ by the NNC controller of Control 2 and the TNC controller of Control 3 (Figs. 41, 42).

Again, by observing Figs. 30 and 40, it can be verified that no chattering occurs in the control torques (except in the Control 2), nor in the linear and angular velocities.

Based on the results of this analysis, it can be said that Control 1 with

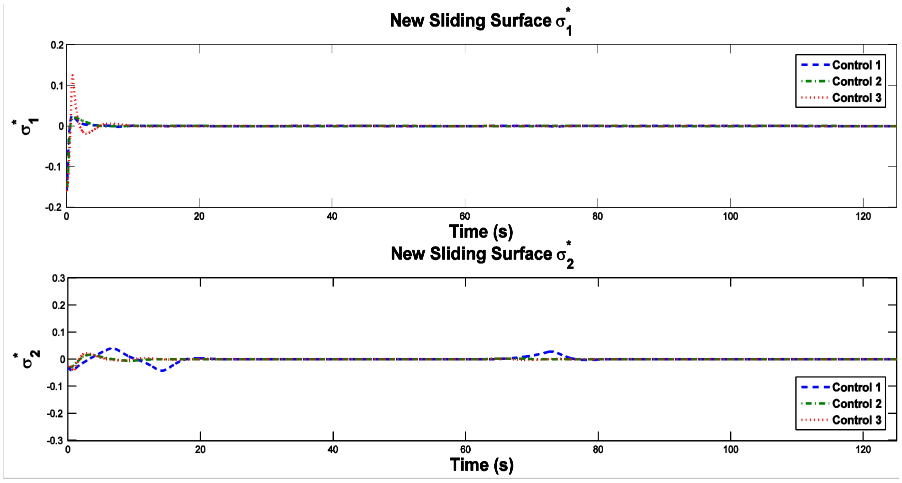

Figure 37. New sliding surfaces using the KNC controller with the neural term

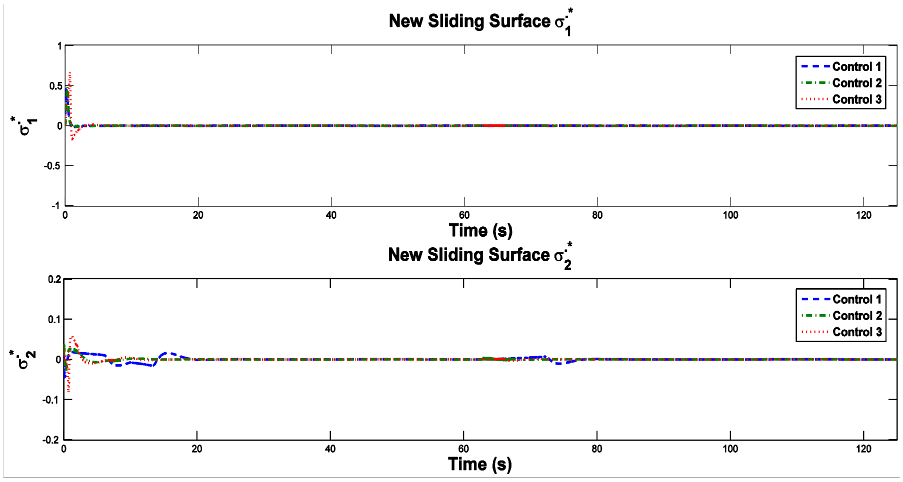

Figure 38. Derivatives of the new sliding surfaces using the KNC controller with the neural term

consideration of the neural term of the KNC controller presents significant robustness under the influence of the disturbances. In Controls 2 and 3, with the same consideration, the robustness is even more significant, because the simulation results in Subsection 4.2 already contained a certain amount of robustness with respect to the incidence of disturbances. Additionally, for Controls 1, 2 and 3, the trajectory tracking is accomplished without penalties in the control efforts. Again, it is emphasized here that Control 2 suffers from and compen-

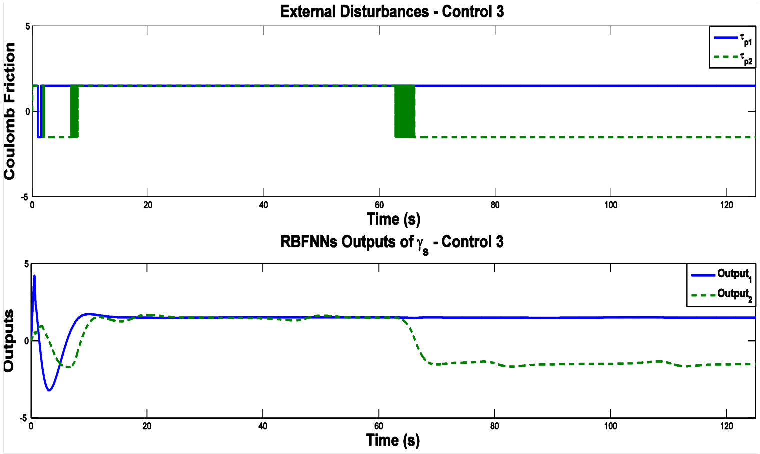

Figure 39. Disturbances (80) and (81) and RBFNN outputs ($\hat{P}_s(s)$) of the robustness term γ_s (65) of the TNC controller of Control 3 using the KNC controller with the neural term

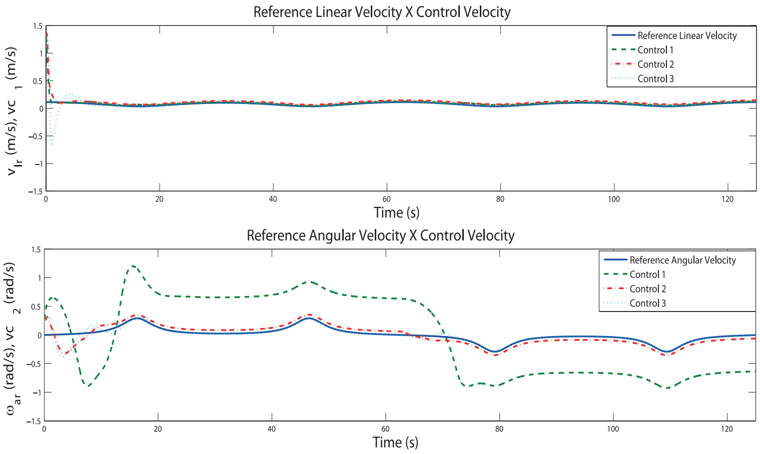

Figure 40. Profile of the velocities using the KNC controller with the neural term

sates for the influence of disturbances through the estimation of the parameters, which may result in the imposition of unnecessary torques to the wheeled mobile robot.

It should be noted that for the NNC controller of Control 2 and TNC controller of Control 3 in all the analyses (Subsections 4.1, 4.2 and 4.3), the weights of the RBFNNs are initialized at zero, both for the estimation of parameters of the inertia matrix and the compensation of the disturbances, without requiring

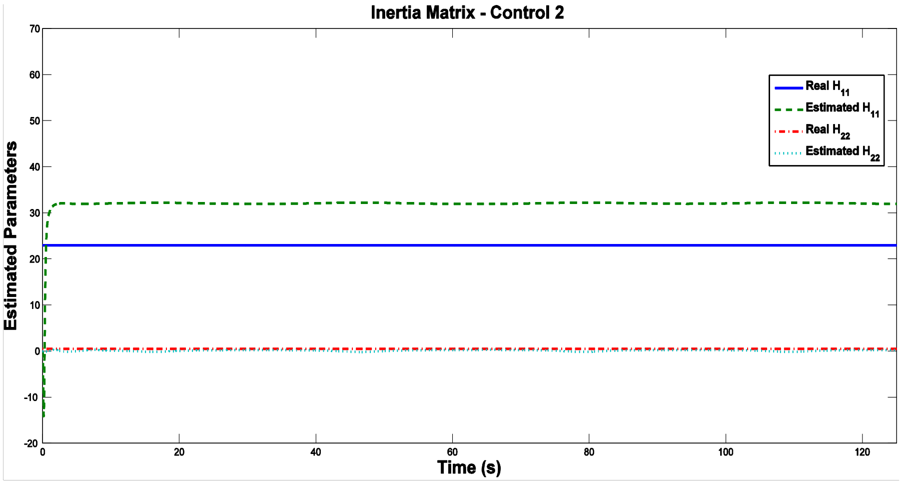

Figure 41. Estimated parameters for the inertia matrix $\bar{H}(q)$ (62) by NNC controller using the KNC controller with the neural term

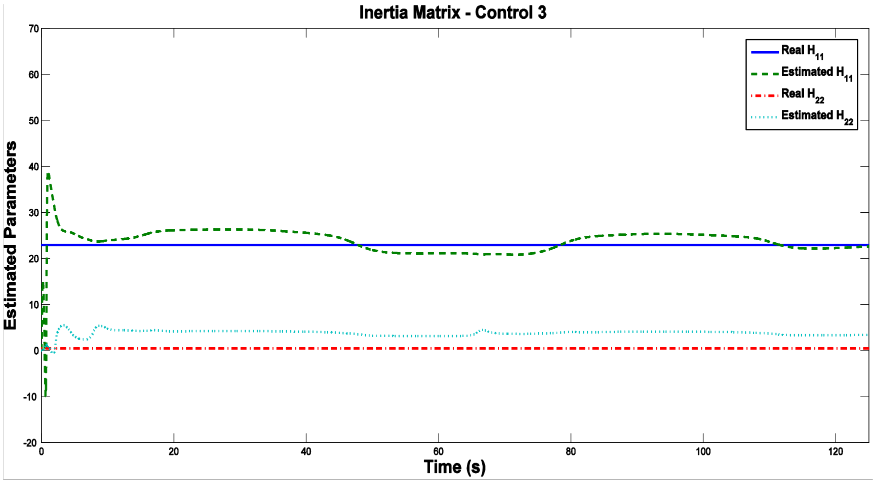

Figure 42. Estimated parameters for the inertia matrix $\bar{H}(q)$ (62) by TNC controller using the KNC controller with the neural term

any knowledge of these parameters and limits of these disturbances, and that training of the RBFNNs is carried out online. Additionally, for the KNC controller in Subsections 4.1, 4.2 and 4.3, the weights of RBFNNs are initialized at zero, and the training of RBFNNs is also carried out online.

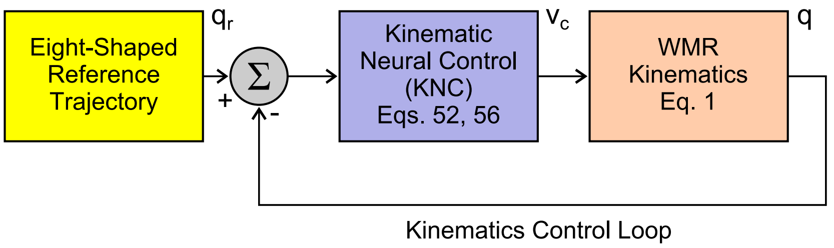

Figure 43. Block diagram of the proposed control structure - KNC controller

5. Conclusions

This work proposed an adaptive neural control algorithm (PANC) that considers uncertainties and disturbances in both the kinematics and dynamics of the model and can be used as an alternative trajectory tracking control technique applied to a wheeled mobile robot.

The implementation of the PANC (KNC and TNC) was based on partitioning of the neural networks into several smaller neural subnets to obtain more efficient computation. This implementation simplifies the design, provides added controller structure, and contributes to faster weight tuning algorithms (i.e., individual partitioned neural networks can be separately tuned). Another advantage of this partitioned neural networks is that if certain terms in the wheeled mobile robots kinematics and dynamics are well known (e.g., inertia matrix $\bar{H}(q)$), then their neural networks can be replaced by deterministic equations. These neural networks can be used to reconstruct only the unknown terms or those too complicated to be computed.

The RBFNNs used in the PANC neither require knowledge of the wheeled mobile robot kinematics and dynamics nor off-line learning. The DNC of the TNC was used to compensate for the wheeled mobile robot dynamics or unknown dynamic parameters, whereas the RNC of the TNC was used to compensate for the bounded unknown disturbances.

The VSC and SMC were considered because the invariance principle is applicable, but this technique exhibits a highly undesirable chattering phenomenon. To avoid such phenomenon, as well as to suppress the bounded unknown disturbances without requiring any prior knowledge of their boundaries, the KNC and RNC of the TNC were used for replacements of the discontinuous components of the classical VSC and SMC. Due to this replacement, the invariance principle was no longer verified. However, robustness is ensured, and a smooth control signal is achieved. The simulation results of the proposed approach were satisfactory.

Stability and convergence of the wheeled mobile robot control system and the learning algorithms for the weights were proven using Lyapunov theory.

The results presented in Section 4 for the integration of the kinematic controller (KNC) and torque controller allow to draw conclusions on the performance of the NNC and TNC controllers with respect to the CTC controller under the influence of disturbances applied in the dynamic model of the wheeled mobile robot.

In fact, the integration of the KNC controller with the CTC controller demonstrated that the incidence of disturbances produces auxiliary velocity tracking errors. These auxiliary velocity tracking errors did not converge to zero; therefore, the CTC controller did not consider the disturbances, and the control effects produced by this controller were not sufficient to compensate for them. Indeed, these auxiliary velocity tracking errors were viewed as disturbances for the kinematic model, and the KNC controller contained the function to compensate such tracking errors, thus driving the convergence of the posture tracking errors to zero and providing for significant robustness in reference trajectory tracking without penalizing the control effects.

The integration of the KNC controller with the NNC controller has ensured the adequate performance with respect to the trajectory, but this may result in the imposition of unnecessary torques to the wheeled mobile robot in order to compensate for the influence of disturbances through the estimation of the parameters.

Because of the integration of the KNC controller, the TNC controller was able to follow the reference trajectory with satisfactory accuracy with incidence of disturbances and without penalizing the control effects. This PANC controller presented a robustness that was even more significant, because the TNC controller performed estimation of the unknown dynamics of the wheeled mobile robot and compensation for the disturbances affecting the wheeled mobile robot, whereas the KNC controller performed compensation for the existing auxiliary velocity tracking errors. It should be noted that different performance qualities could be obtained for this PANC controller by adjusting the adaptation gains, the size of the RBFNNs (number of neurons or number of activation functions in the intermediate layer), and the centers and variances of the GRBFs, in particular.

In short, the simulation results were satisfactory and demonstrated the effectiveness of the KNC with CTC, the KNC with NNC as well as that of the PANC.

The future work will address the validation of the KNC (in the case of kinematic control only, see Fig. 43) and PANC (KNC plus TNC) in real-time applications of a wheeled mobile robot.

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