5
Concluding Remarks

In this work, the modeling and control design of tracked mobile robots (TMRs) is addressed, which are able to perform surveillance tasks in agricultural fields. The proposed methodology has considered that the kinematic model of the TMRs is uncertain due to the inherent slippage between the tracks and the terrain. To deal with the modeling uncertainties and external disturbances, the sliding mode control (SMC) approach was used.

A Mobile User Interface (MUI) based on Android operating system. is developed to control the TMR manually or autonomously. By using the MUI the human operator visualizes the information captured from external and internal sensors. Numerical simulations have been carried out to verify the performance of the controller as well as validate the robot kinematic model.

To the best of the author knowledge, few works in the literature of control and robotics has considered the use of robust control techniques to solve the stabilization and tracking problems of TMRs under their inherent slippage effects on the terrain.

5.1
Discussion

TMRs have a great advantage compared to other locomotion mechanisms: the large area of contact of their tracks give them adaptability to face different types of soil and terrains. However, the modeling of TMRs is a complex task since many authors consider the inherent effect of the track-terrain slippage in different manners into the model. In this work, the slippage has been considered as a time-varying parameter which depends on the square of the robot angular velocity and a terrain roughness coefficient, similar to the modeling of the skid steering mobile robot.

The control problem is formulated by using three different techniques such as: (i) first, a Cartesian space based controller which drives the robot to any desired position, without guaranteeing the desired orientation.

(ii) The second designed controller was based on the Polar coordinates, in which a similarity transformation is applied to the kinematic model ensuring the posture regulation. Then, after the linearization, the resulting control law

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is quite simple and intuitive since it only depends on the posture error. These two control techniques were not able to deal with modeling uncertainties and external disturbances.

(iii) The third controller is based on the sliding mode control approach which provides robustness to kinematic uncertainties, such as uncertainty in the wheel radius and the slippage factor. Simulation results have shown that the classical controllers were not able to ensure a satisfactory performance regarding to the posture error when these are subject to different values of control gains. Indeed, a slightly modification in the gain parameters could lead the system to instability. On the other hand, the robust controller via sliding modes has ensured a remarkable performance in terms of finite time convergence and the robot was always able to reach the desired configuration in spite of changes in the gain parameters.

The Human Robot Interface can help the user in the surveillance task of agricultural fields since by using a mobile device it is possible to control the robot motion remotely, obtain the readings of sensors and images from cameras, visualize the robot localization on the field among others.

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5.2 Future Works

During the development of the present dissertation some challenging issues were not properly addressed and could be investigated in future works:

- Include the dynamic model of the TMRs by using a cascade control strategy to allow the execution of tracking tasks with high speed and fast accelerations;

  The derivation of the dynamic model for the TMR is similar to the robot manipulator case. The main difference is the presence of kinematic nonholonomic constraints on the generalized coordinates, which implies that the linearization of the dynamic model via feedback cannot be achieved. The procedure for deriving, reducing and partially linearizing the robot dynamic model can be found in [2]. Following this formulation, we derive the dynamic model from a n dimensional mechanical system subject to $k < n$ kinematic constraints:

$$\begin{aligned} M(q)\ddot{q} &= G(q)\tau + A(q)\lambda\,, \\ A^T(q)\dot{q} &= 0\,, \end{aligned} \tag{5-1}$$

  where M is the (symmetric and positive definite) inertia matrix of the mechanical system, G is a $(n \times m)$ matrix mapping the $m = n - k$

the external forces τ to generalized forces performing work on q. $A(q)$ is the transpose of the matrix $(k \times n)$ of kinematic constraints of the mechanical system $\lambda \in R^m$ is the vector of Lagrange multipliers, term $A(q)\lambda$ represents the reaction forces at the generalized coordinate level.

Then, the dynamic model of a Tracked Mobile Robot (TMR) is given by: [2]:

$$\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & d\sin\theta \\ \sin(\theta) & -d\cos\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} + \begin{bmatrix} \sin\theta \\ -\cos\theta \\ d \end{bmatrix} \lambda \,, \tag{5-2}$$

$$\dot{x}\sin\theta - \dot{y}\cos\theta + d\dot{\theta} = 0 \,, \tag{5-3}$$

where τ_1 is the driving force, τ_2 is the steering torque, m is the mass of the TMR and I is the moment of inertia around the vertical axis through the center. Thus, the reduced model in state-space is obtained as:

$$\begin{aligned} \dot{q} &= G(q)\,\mathbf{v} \;, \\ \dot{\mathbf{v}} &= M^{-1}(q)\,\tau \;, \end{aligned} \tag{5-4}$$

where:

$$M^{-1}(q) = \begin{bmatrix} \frac{1}{m} & 0 \\ 0 & \frac{1}{I} \end{bmatrix} . \tag{5-5}$$

By using the input transformation:

$$\tau = M\,\mathbf{u} = \begin{bmatrix} m & 0 \\ 0 & I \end{bmatrix} \tag{5-6}$$

Then, the second-order kinematic model is obtained as:

$$\dot{\varepsilon} = \begin{bmatrix} v\cos\theta + d\omega\sin\theta \\ v\sin\theta - d\omega\cos\theta \\ \omega \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} u_1 + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u_2 \;, \tag{5-7}$$

with the state vector $\dot{\varepsilon} = \begin{bmatrix} x & y & \theta & v & \omega \end{bmatrix}^T \in R^5$, where u_1 and u_2 are pseudo-acceleration signals such as $\dot{\mathbf{v}} = \mathbf{u}$ to be properly designed.

- Implement experimental tests for surveillance tasks with a real TMR in agricultural fields in order to verify and validate the robust control

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strategy.

- Design high-order sliding mode controllers (HOSMC), such as super-twisting algorithm, terminal sliding mode algorithm and nested sliding mode algorithm in order to reduce the impact of chattering effect in the ordinary SMC.
- Carry out a proper and rigorous analysis of the robustness for the SMC considering the existence of parametric uncertainty in the TMR model (e.g., radius of wheels) and external disturbance (e.g., wheel-track slip).

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} (r+\delta r)\cos\theta + \gamma\,\sin\theta & d\sin\theta \\ (r+\delta r)\sin\theta + \gamma\,\cos\theta & -d\cos\theta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}, \tag{5-8}$$

where $r > 0$ is the wheel radius, $\delta_r \in \mathbb{R}$ is the uncertainty in the wheel radius, and $\gamma \in [0, 1]$ is the slip between the wheel and track. It is possible to show that dynamic of the chained form takes the form:

$$\begin{aligned} \dot{z}_1 &= u_1\,, \\ \dot{z}_2 &= u_2 + [\delta r + \gamma \sin 2\theta\, v]\,, \\ \dot{z}_3 &= z_2\, u_1 + [-\gamma\, \cos 2\theta\, v]\,. \end{aligned} \tag{5-9}$$

Therefore, the key idea is to demonstrate that the stabilizing control laws, u_1 and u_2, must be properly designed to ensure the robustness properties.

- Develop trajectory planning algorithms and obstacle avoidance techniques to increase the versatility and flexibility of the TMR for autonomous navigation;
- Include computer vision techniques in the MUI to allow face recognition and object detection in order to activate an alarm signal to alert the user that an intruder was detected.
- Study on the usability of the proposed MUI in order to improve its layout to the user and increase the performance.

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