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Robust digital control for autonomous skid-steered agricultural robots

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ABSTRACT

There are two main issues to consider when designing a controller for autonomous off-road vehicles: velocity and terrain irregularities. Whereas the first one is measurable, the second one is very difficult to determine. Solutions to cover these issues could be very complex and difficult to implement in an embedded system with limited resources. The results obtained in our previous research for an adaptive approach implemented in a tractor with varying hitch forces, lead to the improvements presented here. This paper proposes a robust digital RST pole placement controller design for the lateral position, with sensitivity functions tuned to cover uncertainties and non-linearities not considered in the model. Simulations were implemented to assess the performance of the system and the controller implementation was applied to a skid-steered agricultural robot with limited computational resources and a state-of-the-art navigation system, which delivered satisfactory results.

1. Introduction

Skid-steered robots will play an important roll in agricultural robotics due to their flexibility and simple construction. They are suitable for applications such as seeding (Blender et al., 2016), scouting, fertilizing and weed control. Nevertheless, there are some challenges to be covered related not only to the steering system, but also to the interaction with the soil. There are intrinsic non-linearities related to the steering system of such vehicles that make the design of a controller a very complex task. Furthermore, the dynamics of the system are constantly changing due to irregularities on the terrain. There are different approaches for the representation of such systems (Caldwell and Murphey, 2011; Martínez et al., 2005; Wang et al., 2015; Maclaurin, 2011; Guo and Peng, 2013; Yi et al., 2009; Al-Milli et al., 2010; Xueyuan et al., 2013), where different non-linear controllers are applied (Caracciolo et al., 1999; Tchoń et al., 2015; Jun et al., 2014; Pazderskit et al., 2004; Yi et al., 2007; Pazderski and Kozlowski, 2008), some of them being even robust solutions (Arslan and Temeltas, 2011; Inoue et al., 2013). There are also general linear solutions in the literature (Derrick and Bevly, 2008; Derrick and Bevly, 2009; Derrick et al., 2008; Gartley and Bevly, 2008) for controlling the lateral position of off-road vehicles by adapting the controller of the yaw rate with the use of a Model Reference Adaptive System(MRAS). In contrast to the MRAS solution, which requires more effort and filtering, our previous work implements a self-tuning regulator since the error is directly obtained from a least-square identification and a general 2nd-order model can be used in the closed loop. This allows the solution to be applied to different steering systems in a general way. (Fernandez et al., 2018). Nevertheless, this solution still needs a traditional PID to be tuned for the lateral position, which is a time consuming task. Besides, since the identification of this solution requires a rich set of measurements, it could not be ideal for small vehicles with a higher frequency response such a small skid-steered robot. Therefore, the motivation of this research is to find a linear and practical approach for agricultural skid-steered robots to control the lateral position, easy to be programmed into a digital real-time embedded system with limited resources and that also guarantees robustness against uncertainties due to changes in the dynamics of the system.

This paper is divided in four sections. The first part of Section 2 presents an RST pole placement design with tracking and regulation. In the second part (Section 2.2), static parameters used in the controller design are introduced for shaping the sensitivity functions of the closed loop. An experimental setup of a skid-steered robot with its results are presented in Section 3. Finally, the conclusions can be found in Section 4.

2. Material and methods

Generally speaking, the uncertainties in the dynamics of an off-road vehicle are related to the changes in speed and soil irregularities. A

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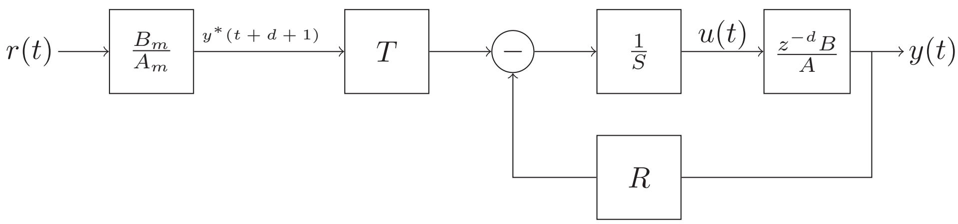

Fig. 1. Digital canonical controller for tracking and regulation.

solution for that is to design a system that considers these uncertainties due to nonlinearities and time varying elements. Here we present a methodology for the design and implementation of a robust digital RST controller using pole placement. There are automatic methods for finding the parameters and shaping the sensitivity functions using convex optimization or H_∞ optimization (Langer and Landau, 1999; Langer and Constantinescu, 1999; Landau and Karimi, 1998). Nevertheless, this section presents a method to control the lateral position of a skid-steered robot by manually shaping the sensitivity functions (Landau and Zito, 2006) due to its simplicity compared to the automatic methods. This also allows for more flexibility in the design and a deep understanding of how the system reacts to changes in the controller design.

2.1. Pole placement: tracking and regulation

A canonical digital controller called RST is shown in Fig. 1. This structure allows one to impose different dynamics by obtaining the polynomials R and S in order to satisfy the desired *regulation performance*. T introduces a *tracking performance* that filters at the same time a desired trajectory $y^*(t+d+1)$ from a tracking model system $\frac{B_m}{A_m}$.

The process to be controlled is represented by $\frac{z^{-d}B}{A}$ and the closed loop function from the desired trajectory y^* to the output y is represented in Eq. (1):

$$H_{CL}(z^{-1}) = \frac{z^{-d}B(z^{-1})T(z^{-1})}{A(z^{-1})S(z^{-1}) + z^{-d}B(z^{-1})R(z^{-1})} \tag{1}$$

where d is the time delay and

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + \ldots + a_{n_A} z^{-n_A} \\ B(z^{-1}) &= b_1 z^{-1} + b_2 z^{-2} + \ldots + b_{n_B} z^{-n_B} \\ S(z^{-1}) &= 1 + s_1 z^{-1} + \ldots + s_{n_S} z^{-n_S} \\ R(z^{-1}) &= r_0 + r_1 z^{-1} + \ldots + r_{n_R} z^{-n_R}. \end{aligned} \tag{2}$$

2.1.1. Regulation

To compute the coefficients R and S of the digital controller we solve a Bezout polynomial equation of the form:

$$P(z^{-1}) = P_D(z^{-1})P_F(z^{-1}) = A(z^{-1})S(z^{-1}) + z^{-d}B(z^{-1})R(z^{-1}). \tag{3}$$

The characteristic polynomial P contains dominant and auxiliary poles. The dominant poles P_D are chosen from the digitalization of a second-order system defined by ω_0 and ζ. The digital auxiliary poles P_F improve the robustness of the controller and are normally smaller (faster) than the real part of the dominant poles. Typical values for the auxiliary poles are $-0.05 \leqslant \alpha_1 \leqslant -0.5$ and α_2 either equals 0 or $\alpha_2 = \alpha_1$. By defining the characteristic equation as follows:

$$P(z^{-1}) = 1 + p_1 q^{-1} + \ldots + p_{np} q^{-np} \tag{4}$$

we obtain R and S by solving

$$x = M^{-1}p \tag{5}$$

where

$$\begin{aligned} x^T &= [1, s_1, \ldots, s_{nS}, r_0, \ldots, r_{nR}] \\ p^T &= [1, p_1, \ldots, p_{np}, 0, \ldots, 0] \end{aligned} \tag{6}$$

and

$$M = \begin{bmatrix} 1 & 0 & \ldots & 0 & 0 & \ldots & \ldots & 0 \\ a_1 & 1 & & . & b_1' & & & \\ a_2 & & & 0 & b_2' & & & b_1' \\ & & & 1 & . & & & b_2' \\ & & & a_1 & . & & & . \\ a_{n_A} & & & a_2 & b_{nB}' & & & . \\ 0 & & & . & 0 & . & . & . \\ 0 & \ldots & 0 & a_{n_A} & 0 & 0 & 0 & b_{nB}' \end{bmatrix}. \tag{7}$$

Here $b_i' = 0$ *for* $i = 0, 1, \ldots, d$ and $b_i' = b_{i-d}$ *for* $i \geqslant d + 1$ and:

$$\begin{aligned} n_A &= degA(z^{-1}) \\ n_B &= degB(z^{-1}) \\ n_S &= degS(z^{-1}) = n_B + d - 1 \\ n_R &= degR(z^{-1}) = n_A - 1 \\ n_P &= degP(z^{-1}) \leqslant n_A + n_B + d - 1. \end{aligned} \tag{8}$$

2.1.2. Tracking

The reference model $H_m = \frac{B_m}{A_m}$ can be used to have an output y that follows a desired trajectory y^* each time a reference r is changed. This tracking model H_m can take the form of a second order system with desired ω_0 and ζ. This leads to choose $T(z^{-1})$ to have a unit static gain between y^* and y and to compensate between regulation dynamics defined by $P(z^{-1})$ and tracking dynamics defined by the poles of the reference model (Am):

$$T(z^{-1}) = G * P(z^{-1}) \tag{9}$$

where

$$G = \begin{cases} 1/B(1) & if \quad B(1) \neq 0 \\ 1 & if \quad B(1) = 0. \end{cases} \tag{10}$$

Having R, S, T and a desired trajectory y^* we obtain a control law of the form:

$$S(z^{-1})u(t) + R(z^{-1})y(t) = T(z^{-1})y^*(t + d + 1). \tag{11}$$

2.2. Robust pole placement design

In order to consider uncertainties in our control design, the structure of Fig. 1 can be extended into Fig. 2 where $p(t)$ are disturbances, $b(t)$ is noise and $v(t)$ disturbances on the plant input.

We can obtain then the following *output, input, noise*, and *disturbance sensitivity functions* respectively:

$$\begin{aligned} S_{yp}(z^{-1}) &= \frac{A(z^{-1})S(z^{-1})}{A(z^{-1})S(z^{-1}) + B(z^{-1})R(z^{-1})} \\ S_{up}(z^{-1}) &= \frac{-A(z^{-1})R(z^{-1})}{A(z^{-1})S(z^{-1}) + B(z^{-1})R(z^{-1})} \\ S_{yb}(z^{-1}) &= \frac{-B(z^{-1})R(z^{-1})}{A(z^{-1})S(z^{-1}) + B(z^{-1})R(z^{-1})} \\ S_{yv}(z^{-1}) &= \frac{B(z^{-1})S(z^{-1})}{A(z^{-1})S(z^{-1}) + B(z^{-1})R(z^{-1})}. \end{aligned} \tag{12}$$

As we can see, the common denominator happens to be the characteristic equation of the closed loop system of Eq. (1). The *noise sensitivity function* S_{yb} with a negative sign is also known in the literature as