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Linear Controller Design for Autonomous Car Steering

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Contents

LINEAR CONTROLLER DESIGN FOR AUTONOMOUS CAR STEERING

1 Introduction

The present report addresses the design of a linear controller for autonomous steering of a non-holonomic vehicle along a guideline. If the lateral deviation of the vehicle from the guidline and the guidline curvature are available from measurement, a method of autonomous car steering was developed in our previous report [1]. However, this method does not operate satisfactory in some cases because the lateral deviation rate can not be set arbitrarily. The present report proposes to solve this problem by means of introducing an additional feedback on the yaw rate of the vehicle. This allows us to set an arbitrary decrease rate of the lateral deviation if there are no constraints of the steering angle. The better performance is also achieved if there exist constraints of the steering angle.

The report is organized as follows. The classical single-track model of the steering dynamics is described in section 2 where the control goal is formulated. In order to indicate the drawbacks of our previous controller with a feedback on the lateral deviation, this controller is described in section 3. A linear controller with an additional feedback on the yaw rate is presented in section 4. The constraints of the steering angle and a necessary condition for the existence of a linear controller for autonomous car steering with the saturated steering angle is obtained in section 5. The theoretical results are verified by on-going simulation. The main theoretical contribution of the present report is described in section 6 where a general problem of the controller design with system output regardless to external disturbances is considered. The controller design for autonomous car steering is a very special case of a general problem of time-varying feedback control of a plant considered in section 7. Conclusions are given in section 8.

2 Model of the vehicle's dynamics and control problem statement

The classical single-track model of the car steering dynamics is used [2, 3]. This model is obtained by lumping the two front wheels in the centerline of the vehicle, the same is done with the rear wheels [2].

The following notations are used in the present report: $\bar{v}$ – is a velocity vector at the center of gravity (CG) of the vehicle, its magnitude is $v > 0$; β – is a sideslip angle between the centerline of the vehicle and $\bar{v}$; r – is a yaw rate; $\Delta\psi$ – is an angle between the centerline of the vehicle and a tangent to the guideline; y – is a lateral deviation of the position sensor from the guideline; u – is a steering angle. A curvature of the guideline at the nearest point to the vehicle's position sensor is denoted by ϕ (according to the notations of [2], while u and ϕ correspond to δ_f and ρ_{ref} in [2] respectively).

The following equation describes the vehicle dynamics while tracking a reference path [2, 3]:

$$\frac{dx}{dt} = Ax + Bu + D\phi, \tag{2.1}$$

where $x = [\beta, r, \Delta\psi, y]^T$, $B = [b_{11}, b_{21}, 0, 0]^T$, $D = [0, 0, -v, 0]^T$,

$$A = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ v & l_s & v & 0 \end{bmatrix},$$

$$\begin{array}{ll} a_{11} = -(c_r + c_f)/\widetilde{m}v, & a_{12} = -1 + (c_r l_r - c_f l_f)/\widetilde{m}v^2, \\ a_{21} = (c_r l_r - c_f l_f)/\widetilde{J}, & a_{22} = (c_r l_r^2 + c_f l_f^2)/\widetilde{J}v, \\ b_{11} = c_f/\widetilde{m}v, & b_{21} = c_f l_f/\widetilde{J}. \end{array}$$

The mass m and moment of inertia J of the vehicle are normalized by the road adhesion factor μ, i.e. $\widetilde{m} = m/\mu$, $\widetilde{J} = J/\mu$.

The lateral deviation y and the guidline curvature ϕ are supposed to be measured by the sensors mounted onto the vehicle. The yaw rate r is measured by a gyroscope.

The steering angle u is limited: $|u| \leq C_u$. The curvature ϕ of the guideline is also bounded: $|\phi| \leq C_\phi$. Values C_u and C_ϕ must be coordinated in order to allow the vehicle to follow the quideline. The detailed analysis of the relation between C_u and C_ϕ will be given further.

Control problem statement. The steering system of the vehicle has to drive the lateral deviation y to zero:

$$y(t) \to 0 \quad \text{while} \quad t \to \infty \tag{2.2}$$

for any $\phi(t)$. The steering system operates with $y(t)$ and $\phi(t)$ as its inputs. In the the yaw rate is measured, $r(t)$ can also be used.

3 Design of a linear controller utilizing only lateral deviation feedback

In order to design a controller for the goal (2.2), the dynamics equation (2.1) is transformed into the operator form with the inputs u, ϕ and the output y:

$$s^2\Delta(s)y = n(s)u - v^2\Delta(s)\phi, \tag{3.1}$$

where $s = d/dt$ is the differentiation operator.

Coefficients of polynomials $\Delta(\lambda) = \lambda^2 + \Delta_1\lambda + \Delta_0$, $n(\lambda) = n_2\lambda^2 + n_1\lambda + n_0$ are defined according to formulae [2]:

$$\Delta_1 = -a_{11} - a_{22}, \quad \Delta_0 = a_{11}a_{22} - a_{21}a_{12},$$

$$n_2 = b_{11}v + b_{21}l_s, \quad n_0 = b_{11}a_{21} - b_{21}a_{11},$$

$$n_1 = b_{11}(a_{21}l_s - a_{22}v) + b_{21}(v(a_{12}+1) - a_{11}l_s).$$

If y and ϕ are measured, the controller was obtained in our previous report [1] in the form

$$n(s)u - v^2\Delta(s)\phi = e(s)y, \tag{3.2}$$

where $e(\lambda) = e_2\lambda^2 + e_1\lambda + e_0$ is such that a polynomial $f(\lambda) = \lambda^2\Delta(\lambda) - e(\lambda) = \lambda^4 + f_3\lambda^3 + f_2\lambda^2 + f_1\lambda + f_0$ is stable. The controller (3.2) cancels a ϕ-dependent dynamics of y and sets y to satisfy the equation $f(s)y = 0$. Therefore, $y(t)$ tends to zero exponentially. The characteristic polynomial of the closed-loop system (2.1), (3.2) is $X(\lambda) = f(\lambda)n(\lambda)$. Thus, if $n(\lambda)$ is stable (system (2.1) is minimum-phase), then the controller (3.2) stabilizes the system (2.1) for any continuous $\phi(t)$. According to [4], the last condition is also sufficient for the system (2.1), (3.2) in order to achieve the goal (2.2) while utilizing y and ϕ only.

The coefficients f_0, f_1, f_2 are set by means of choosing the controller parameters e_0, e_1, e_2. In particular, $f_2 = \Delta_0 - e_2$, $f_1 = -e_1$, $f_0 = -e_0$. According to the Hurwitz criterion, the polynomial $f(\lambda)$ is stable if and only if

$$f_1f_2f_3 - f_1^2 - f_3^2f_0 > 0 \quad \text{and} \quad f_i > 0, \quad i = 0, 1, 2, 3. \tag{3.3}$$

The set of triples (f_0, f_1, f_2) satisfying the inequalities (3.3) for a given value of $f_3 > 0$ is not empty, e.g. a triple $f_0 = 1$, $f_1 = 1$, $f_2 = 2(1 + f_3^2)/f_3$ belongs to this set. Another example corresponds to fixed values of $f_2 > 0$ and $f_3 > 0$. In this case, the coefficients f_0 and f_1 must satisfy the following inequalities: $0 < f_1 < f_2f_3$, $0 < f_0 < f_1(f_2f_3 - f_1)/f_3^2$.

The decrease rate of the lateral deviation y depends on the root locus of $f(\lambda)$ which can not be chosen arbitrarily (because the first two coefficients of $f(\lambda)$ are already set and they can not be changed). However, an additional feedback on the yaw rate (if it is available from measurement) allows us to solve this problem.

4 Design of a linear controller with an additional feedback on the yaw rate

The feedback on the yaw rate is introduced according to the formula

$$u = \tilde{u} + k_r r, \tag{4.1}$$

where $\widetilde{u}$ is a modified control input, and k_r is the yaw rate feedback gain. The choice of k_r will be described further. By means of substituting (4.1) into (2.1) with the new modified input $\widetilde{u}$ it is obtained:

$$\frac{dx}{dt} = \widetilde{A}x + B\widetilde{u} + D\phi, \tag{4.2}$$

where

$$\widetilde{A} = \begin{bmatrix} a_{11} & a_{12} + k_r b_{11} & 0 & 0 \\ a_{21} & a_{22} + k_r b_{21} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ v & l_s & v & 0 \end{bmatrix}.$$

Rewrite the last equation in the operator form with the inputs $\widetilde{u}$, ϕ and the output y:

$$s^2(\Delta(s) - k_r(b_{21}s + \alpha))y = n(s)\widetilde{u} - v^2(\Delta(s) - k_r(b_{21}s + \alpha))\phi, \tag{4.3}$$

where $\alpha = a_{21}b_{11} - a_{11}b_{21}$. Using the results of section 6 (see also [5]) we can describe the whole family of the linear controllers which provide to achieve the control goal (2.2). We consider the design of a controller similar to the controller (3.2):

$$n(s)\widetilde{u} - v^2(\Delta(s) - k_r(b_{21}s + \alpha))\phi = e(s)y, \tag{4.4}$$

where $e(\lambda)$ is such that $f(\lambda) = \lambda^2(\Delta(\lambda) - k_r(b_{21}\lambda + \alpha)) - e(\lambda)$ is stable. The controller (4.1), (4.4) ensures that the lateral deviation y satisfies the equation

$$f(s)y = 0.$$

By means of an appropriate choice of k_r, e_0, e_1, e_2, the coefficients of the polynomial $f(\lambda)$ can be chosen arbitrarily. In particular, let $f(\lambda) = \lambda^4 + f_3\lambda^3 + f_2\lambda^2 + f_1\lambda + f_0$ be any desired polynomial. Parameters e_0, e_1, e_2 and k_r corresponding to the polynomial $f(\lambda)$ are defined according to the following formulae:

$$k_r = (\Delta_1 - f_3)/b_{21}, \quad e_2 = \Delta_0 - k_r\alpha - f_2, \tag{4.5}$$

$$e_1 = -f_1, \quad e_0 = -f_0. \tag{4.6}$$

Thus, the controller (4.1), (4.4) with the appropriately chosen parameters allows for an arbitrary set of the decrease rate of the lateral deviation y.

One should note that the linear controllers (3.2) and (4.1), (4.4) do not take into account the constraints on the steering angle.

5 Constraints analysis

As it was mentioned above, the constraint on the steering angle magnitude must be coordinated with the maximum value of the guideline curvature. To determine the upper bound of the curvature from a given constraint on u, let us consider the motion along a guideline with a constant curvature $\phi \equiv \phi_{const}$. Let some linear controller stabilize the system so that after a transient period $y \approx \dot{y} \approx .. y^{(4)} \approx 0$ and $u \approx$ const. Thus, it follows from (3.1) that $n_0 u = v^2 \Delta_0 \phi_{const}$ and $|u| = |v^2 \Delta_0 / n_0||\phi_{const}| \le C_u$. In order the last inequality be satisfied, the curvature ϕ_{const} must be less then $C_\phi = C_u |n_0 / v^2 \Delta_0|$. Hence, the necessary condition for a linear controller to stabilize the system (2.1) with the saturation of the steering angle $|u| \le C_u$ for any continuous $\phi(t)$ is

$$|\phi| \le C_\phi = C_u |n_0 / v^2 \Delta_0|. \tag{5.1}$$

However, the condition (5.1) is not satisfied in the case of the motion along a curve of a small radius. The radius of the guideline must be greater than C_ϕ^{-1}. A problem arises if we wish to find a domain in the parameter space such that the control goal (2.2) is fulfilled for the considered nonlinear system with the saturation-line nonlinearity. The solution can be obtained by using our results described in [6, 7] (we omit here this analysis). Our results described in [8] are used for the case of a variable velocity of the vehicle.

6 General problem of the controller design with a system output regardless to external disturbances

Consider a general system "plant"–"controller":

$$A(s)y(t) = B(s)u(t) + F(s)\varphi(t), \tag{6.1}$$

$$C(s)y(t) = D(s)u(t) + G(s)\varphi(t), \tag{6.2}$$

where $u(t) \in \mathbb{R}^m$ is the control input, $y(t) \in \mathbb{R}^m$ is the system output, and $\varphi(t) \in \mathbb{R}^k$ denotes the external disturbance, A, B, C, D, F, G are real matrix polynomials of the corresponding dimensions, $\det A \not\equiv 0$, $\det B \not\equiv 0$, $\deg A \ge \deg B$, $\deg A \ge \deg F$ ($\deg A$ denotes a degree of the matrix polynomial A), $0 \le t < \infty$, $s = d/dt$. Let us introduce the characteristic polynomial of the system (6.1), (6.2) as

$$\Xi(\lambda) = \begin{bmatrix} A(\lambda) & -B(\lambda) \\ -C(\lambda) & D(\lambda) \end{bmatrix}. \tag{6.3}$$

The controller (6.2) is called *stabilizing* if $\Xi(\lambda)$ is a Hurwitz matrix polynomial (i.e. $\det \Xi(\lambda)$ is Hurwitz) and $\det D(\lambda) \not\equiv 0$. The controller (6.2) is called *I-universal* (i.e. universal by the property of invariance) if it is stabilizing and $|y(t)| \to 0$ while $t \to +\infty$ for any $\varphi(t)$ and for any solution of (6.1), (6.2). It is simple to prove that the I-universality is equivalent to the stability while the condition $W_y(\lambda) \equiv 0$ holds, where $W_y(\lambda)$ is a transfer function from φ to y.

We suppose that the plant (6.1) is given. The problem is to design an I-universal controller and describe a set of all I-universal controllers.

The design of a controller for autonomous car steering considered in the previous sections is a very special case of this general problem solved in [4] for a stable and minimum-phase plant. Now, we consider the case of a minimum-phase plant without a supposition that it is stable (i.e. a polynomial $\det A(\lambda)$ may be unstable). Remark that the plant (4.3) is unstable in the problem of autonomous car steering (except of the special case described in our previous report [1]).

Two controllers (6.2) with the coefficients $[C_1, D_1, G_1]$ and $[C_2, D_2, G_2]$ are called *$\mathcal{H}$-equivalent* (Hurwitz equivalent) if there exist matrix polynomials $H_1(\lambda)$ and $H_2(\lambda)$ such that $H_1^{-1}[C_1, D_1, G_1] = H_2^{-1}[C_2, D_2, G_2]$.

We apply the following result [5].

Lemma 1. *Suppose that* (6.1) *is the minimum-phase plant (that is $B(\lambda)$ is a Hurwitz matrix polynomial).*

1) *Let $R(\lambda)$ be the Hurwitz $(m \times m)$-matrix polynomial, $r(\lambda)$ be an arbitrary $(m \times m)$-matrix polynomial,* $\det r(\lambda) \not\equiv 0$. *The controller* (6.2) *with the coefficients*

$$C(s) = r(s)A(s) - R(s), \qquad D(s) = r(s)B(s) \tag{6.4}$$

is stabilizing and for this controller $\det \Xi(\lambda) = detB(\lambda) \det R(\lambda)$.

2) *Any other stabilizing controller* (6.2) *is $\mathcal{H}$-equivalent to the controller with the coefficients* (6.4) *for some r and R of the mentioned form. It is possible to choose $R(\lambda) = \rho(\lambda) I_m$ where $\rho(\lambda)$ is a scalar Hurwitz polynomial.*

Corollary. If $A(\lambda) = \lambda^q A_q + \ldots + A_0$, $\det A_q \neq 0$ in (6.1), then for any positive integer N there exists a stabilizing controller with the coefficients (6.4) such that $\deg D \geq \deg C + N$.

If $K \geq \deg A - \deg B + N - 1$ and R is an arbitrary Hurwitz matrix polynomial such that $\deg R = K + q$, then there exists a matrix polynomial r such that $\deg r = K$, $\deg(rA - R) \leq q - 1$ and it is defined uniquely. Hence, the following condition holds: $\deg D - \deg C \geq K + \deg B - (q - 1) \geq N$.

The statement 1) of Lemma 1 can be verified directly by using the Schur's Lemma. The statement 2) can be proved similarly to the proof of theorem 1 in [4].

Let us summarize the main result of this section (this result is proved in [5]).

Theorem 1. 1) *Let* (6.2) *be the stabilizing controller. It will be the I-universal controller if and only if the matrix $D(\lambda)B(\lambda)^{-1}F(\lambda)$ is a polynomial and $G(\lambda) = D(\lambda)B(\lambda)^{-1}F(\lambda)$.*

2) *Let $B(\lambda)$ be the Hurwitz matrix polynomial, $R(\lambda)$ be an arbitrary Hurwitz $(m \times m)$-matrix polynomial, $r(\lambda)$ be an arbitrary $(m \times m)$-matrix polynomial,* $\det r(\lambda) \not\equiv 0$. *The controller* (6.2) *with the coefficients*

$$C(s) = r(s)A(s) - R(s), \quad D(s) = r(s)B(s), \quad G(s) = r(s)F(s) \tag{6.5}$$

is the I-universal controller. For this controller $R(s)y(t) = 0$ and $W_u(\lambda) = -B(\lambda)^{-1}F(\lambda)$, where $W_u(\lambda)$ is a transfer function from φ to u. Any other I-universal controller is $\mathcal{H}$-equivalent to the controller with the coefficients (6.5) *for some R and r of the mentioned form. It is possible to choose $R = \rho(\lambda) I_m$, where $\rho(\lambda)$ is a scalar Hurwitz polynomial.*

One should note that the transfer function $W_u(\lambda)$ does not depend on the choice of the I-universal controller.

If we design a controller which does not rely on the measurement of external disturbance, then $G(s) \equiv 0$ in (6.2). Using theorem 1 we obtain the following.

Corollary. If there is no measurement of external disturbance, then the absolute invariance is impossible: the I-universal controller with $G(s) \equiv 0$ does not exist.

In this statement, the external disturbance $\varphi(t)$ is an arbitrary function. If φ belongs to some class $\mathbb{M}$ of functions, then it is possible to design a controller which does not rely on the measurement of φ and the output does not depend on $\varphi \in \mathbb{M}$. If, for example, $\mathbb{M}$ is a class of piece-linear functions, then the controller (6.2) with the coefficients (6.5) has the mentioned property if $G(\lambda) = \lambda^2 G_0(\lambda)$ and $\deg D(s) \geq \deg G(s)$.

7 Synthesis of a controller for a time-varying model of an autonomous vehicle

The Ackermann's model (2.1) of an autonomous vehicle is considered [2, 3]. However, the velocity is supposed to be a time-varying piece-linear function. The vehicle performs an autonomous tracking of a guideline. The deviation y of the vehicle's CG from the guidline is measured during the motion (the whole path is unknown beforehand). The autonomous car steering is achieved by a controller which drives y to zero.

The vehicle is described by a fourth-order equation, and y is one of its phase coordinates. Only two of these coordinates can be measured directly. The controller design for autonomous car steering involves two parts: (1) – a compensator synthesis for the first three coordinates in order to provide their estimations, (2) – a design of a stabilizing controller for y. The estimation and control problems are solved by means of similarity transformations.

Let us focus on the design of the stabilizing controller while assuming that estimations of the unmeasured coordinates are known. Since the considered system is time varying, we apply a transformation $Z(t) = T(t)x(t)$ where a matrix T is obtained from the following conditions: the transformed system's matrix has a Frobenius form with the last functional line, the control allocation vector of the transformed system is the last singular orth e_n. The matrices

$$\begin{aligned} \widetilde{B}(t) &= T(t)B(t), \\ \widetilde{A}(t) &= T(t)A(t)T^{-1}(t) + \frac{dT(t)}{dt}T^{-1}(t) \end{aligned} \tag{7.1}$$

are obtained according to the procedure described in [8]. The stabilization of this system in a Frobenius form is performed. The admissible ranges of the feedback vector of the transformed system are found from a square equation. The coefficients of this equation are functions of the velocity v and its derivatives (the higher derivatives can be neglected due to the physical properties of the system). Thus, for each pair of the values (v, a), where v denotes a velocity and a – an acceleration, the upper and lower boundaries of the feedback vector of the transformed system are evaluated. Then, a table of the feedback coefficients of the transformed system and the similarity transformation matrices for the appropriate ranges of v and a are computed.

The stabilizing controller constructed by means of this procedure provides the feedback in the Luenberger's estimator of the unmeasured coordinates and it stabilizes the vehicle's motion along the guidline.

The operation of the stabilizing controller developed was verified by simulation in Simulink and Matlab. The stationary and time-varying modes were simulated. The stationary mode was tested on two maneuvers performed at a constant velocity: (1) – motion along a circular guidline (zero initial conditions) and (2) – tracking a straigt line (non-zero initial conditions). The time-varying mode was tested on a turning maneuver performed at a constant velocity during the turn. The simulation results have shown that the proposed controller stabilizes the motion when the vehicle's parameters are stationary and time-varying within the known bounds. The results of this section are presented in details in [8, 9, 10].

8 Conclusion

The problem of autonomous car steering along a guideline and its generalization were considered. The previously designed controller (that relies on the lateral deviation feedback y only) does not provide an arbitrary decrease rate of the lateral deviation y. The operation of the controller was improved by means of introducing an additional feedback on the yaw rate r and using our new theoretical results described in section 6. The lateral deviation satisfies the equation $f(s)y = 0$, where the roots of the polynomial $f(\lambda)$ can be chosen arbitrarily by means of the appropriate choice of the controller's parameters. The effectiveness of the new controller has been verified by means of simulation in Simulink and Matlab. The controller ensures the accurate tracking of the guidline in various maneuvers while the vehicle's parameters are within a known range. The necessary condition for existence of a linear controller is obtained in the scope of the problem of autonomous car steering with the saturated steering angle.

The similar general problems of the controller design with the system output regardless to external disturbances are considered. Our main research results are published in [7, 10], they will also be presented in [5, 8, 9, 11, 12, 13]. The final results of this project will be described in our paper [14].

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