Abstract: In this contribution linear dynamic output feedback is used to achieve stable tracking for nonlinear flat systems. To this end a time varying differential operator representation resulting from a linearization of the plant about the reference trajectory is used. The control scheme is illustrated for a uniaxial vehicle model.
back controllers is presented which amounts to solving a time varying Diophantine equation. In Section 5 the introduced control scheme is applied to a uniaxial vehicle model. This example also demonstrates that the control scheme can easily be extended to dynamic feedback linearizable systems.

2. DIFFERENTIAL OPERATOR REPRESENTATION OF NONLINEAR FLAT SYSTEMS

2.1 Transformation to nonlinear controller form

Consider the following nth order nonlinear flat system

\[ \dot{x} = f(x) + g(x)u \]
\[ y = h(x) \]

with \( m \) inputs \( u \) and \( m \) outputs \( y \). If system (1)–(2) is static feedback linearizable (Isidori, 1995), then the definition of flatness simplifies to the following form: there exists a flat output \( y_f = \Phi(x) \)

\[ \text{with dim}(y_f) = \text{dim}(u) \text{ such that} \]
\[ x = \psi_z(y_f, \dot{y}_f, ..., y_f^{(\beta)}) \]
\[ u = \psi_u(y_f, \dot{y}_f, ..., y_f^{(\beta+1)}) \]

By setting \( \beta + 1 = (\kappa_1, ..., \kappa_m) \) and introducing the (Brunovsky) states (Delaleau and Rudolph, 1998)

\[ z = [z_1, ..., z_{\kappa_1}, ..., z_{\kappa_1}, ..., z_{\kappa_m}, ..., z_{\kappa_m}]^T \]
\[ = [y_1, ..., y_{\kappa_1}, ..., y_{\kappa_1}, ..., y_{\kappa_m}, ..., y_{\kappa_m}]^T \]

system (1) can be transformed via the diffeomorphism

\[ x = \psi_z(z) \]

into the controller form (Isidori, 1995)

\[ z^* = a(z) + B(z)u \]

\[ \text{where} \]
\[ z^* = [z_{\kappa_1}^1, ..., z_{\kappa_m}^m]^T \]
\[ a(z) = [a_1^1(z), ..., a_m^m(z)]^T \]
\[ b_i^j(z) = [b_i^1(z), ..., b_i^m(z)]^T, \quad i = 1(1)m \]

Linearizing (12) about \( (z_d, u_d) \) results in

\[ \Delta z^* = A(t)\Delta z + B(t)\Delta u \]

with \( \Delta z^* = z^* - z_d^* \), \( \Delta z = z - z_d, \Delta u = u - u_d \) and the matrices

\[ A(t) = \left. \frac{\partial(a(z) + B(z)u)}{\partial z} \right|_{z_d, u_d} \]
\[ B(t) = B(z_d(t)) \]

Using the differential operator \( D = \frac{d}{dz} \), \( \Delta z^* \) can be expressed as

\[ \Delta z^* = \text{diag}(D^{\kappa_1})\Delta y_f \]

where \( \Delta y_f = y_f - y_{f,d} \). Introducing the blockdiagonal matrix

\[ S(D) = \text{diag}([1, ..., D^{\kappa_1-1}]^T, ..., [1, ..., D^{\kappa_m-1}]^T) \]

it is furthermore possible to write

\[ \Delta z = S(D)\Delta y_f \]

With (20) and (22) equation (17) reads

\[ \text{diag}(D^{\kappa_1})\Delta y_f = A(t)S(D)\Delta y_f + B(t)\Delta u \]

As the the controller form (9) is well defined in a neighbourhood of \( z_d \) by assumption, \( B(z) \)
(see (12)) is invertible in a neighbourhood of the trajectory $z_d$ (Isidori, 1995). Consequently, $B(t)$ is nonsingular for $t \in [0, T]$ (see (19)) and thus (23) can be rearranged in the form

$$B^{-1}(t) (\text{diag}(D^{\kappa_i}) - A(t)S(D)) \Delta y_f = \Delta u \quad (24)$$

A linearization of (10) in the $z$-coordinates about $z_d$ yields with $\Delta y = y - y_d$

$$\Delta y = \frac{\partial h(z)}{\partial z} \bigg|_{z_d} \Delta z = C(t)S(D) \Delta y_f \quad (25)$$

where (22) was used. By introducing the polynomial matrices $N(D, t)$ and $Z(D, t)$ according to

$$N(D, t) = B^{-1}(t) (\text{diag}(D^{\kappa_i}) - A(t)S(D)) \quad (26)$$

$$Z(D, t) = C(t)S(D) \quad (27)$$

(see (24) and (25)) one finally obtains the linear time varying differential operator representation

$$N(D, t) \Delta y_f = \Delta u \quad (28)$$

$$\Delta y_f = Z(D, t) \Delta f \quad (29)$$

Note that (28) is a differential equation for $\Delta y_f$. The trajectory planning has to ensure that the elements of the matrices $A(t)$, $B^{-1}(t)$ and $C(t)$ are sufficiently smooth functions of time, such that by (26) and (27) the coefficients of $N(D, t)$ and $Z(D, t)$ are sufficiently smooth. With $\Gamma_c[N(D, t)]$ denoting the highest degree matrix and $\delta_{ci}[N(D, t)]$ the $i$th column degree (Wolovich, 1974), $N(D, t)$ in (26) can be expressed as

$$N(D, t) = \Gamma_c[N(D, t)] \text{diag}(D^{\kappa_i}[N(D, t)]) + N_R(D, t) \quad (30)$$

with $N_R(D, t)$ a polynomial matrix of lower degrees. Comparing (30) with (26) yields the following relations

$$\Gamma_c[N(D, t)] = B^{-1}(t) \quad (31)$$

$$\delta_{ci}[N(D, t)] = \kappa_i, \quad i = 1(1)m \quad (32)$$

where (31) and (32) are implied by the nonlinear controller form (8)–(9) and are satisfied for $t \in [0, T]$. This shows that $N(D, t)$ is column reduced (Wolovich, 1974), i.e. $\text{det} \Gamma_c[N(D, t)] \neq 0$ for $t \in [0, T]$.

If the system (1)–(2) is not static feedback linearizable, it is always possible to introduce controller states (based on the differential parameterization (4)–(5)) such that the resulting system is static feedback linearizable. Then the differential operator representation can be derived as described above (see the example in Section 4 for details).

### 3. DESIGN OF LINEAR TRACKING CONTROLLERS

#### 3.1 Time varying flat feedback

If external disturbances or modelling errors affect the tracking behaviour, a tracking controller is needed to stabilize the tracking. This the more, when the feedforward $u_d$ is applied to the system (1)–(2), the dynamics of the tracking error $\Delta y_f = y_f - y_{f.d}$ in a neighbourhood of the trajectory is governed by the differential equation

$$N(D, t) \Delta y_f = 0 \quad (33)$$

The error dynamics (33) are time varying and might be too slow or even unstable, depending on the system (1)–(2) and the trajectory $y_{f.d}$. In order to assign a desired time invariant dynamics for the tracking error consider an additional control action $\Delta u$ (see (28)) in the form

$$\Delta u = \Gamma_c[N(D, t)] \bar{u} + N_R(D, t) \Delta y_f \quad (34)$$

with new input $\bar{u}$. Applying (34) to the differential operator representation (28) yields the time invariant dynamics

$$\text{diag}(D^{\kappa_i}) \Delta y_f = \bar{u} \quad (35)$$

in view of (30). Via the new input $\bar{u}$ it is possible to assign the stable time invariant dynamics

$$\text{diag}(\bar{n}_i(D)) \Delta y_f = 0 \quad (36)$$

with the Hurwitz polynomials

$$\bar{n}_i(D) = D^{\kappa_i} + \bar{a}_{i,1}D^{\kappa_{i-1}} + \ldots + \bar{a}_{i,0} \quad (37)$$

to the tracking error $\Delta y_f$, by setting

$$\bar{u} = -\text{diag}(\bar{n}_i(R(D))) \Delta y_f \quad (38)$$

Substituting (38) in (34) yields the corresponding time varying flat feedback

$$\Delta u = -\Gamma_c[N(D, t)] \text{diag}(\bar{n}_i(R(D))) \Delta y_f + N_R(D, t) \Delta y_f \quad (39)$$

Adding

$$\Gamma_c[N(D, t)] \text{diag}(D^{\kappa_i}) \Delta y_f \ldots$$

$$\ldots - \Gamma_c[N(D, t)] \text{diag}(D^{\kappa_i}) \Delta y_f \quad (40)$$

to (39) leads to the more compact formulation

$$\Delta u = (N(D, t) - \bar{N}(D, t)) \Delta y_f \quad (41)$$

with the polynomial matrix

$$\bar{N}(D, t) = \Gamma_c[N(D, t)] \text{diag}(\bar{n}_i(D)) \quad (42)$$

The tracking controller design results in the overall control law

$$u = u_d + \Delta u \quad (43)$$
With this control strategy only the the feedforward $u_d$ (see (11)) is applied when the system (1)–(2) exactly tracks the reference trajectory $y_{f,d}$ (i.e. $\Delta y_f = 0$).

### 3.2 Dynamic time varying output feedback

If the tracking error $\Delta y_f$ or its time derivatives are not available for measurement, the flat feedback (41) can at least be estimated by a time varying output feedback. In the following, a generally applicable approach to this problem is described resulting in a dynamic feedback controller of relatively high order. However, in some cases and for specific assignments for the dynamics of the tracking error $\Delta y_f$ (36) it may also be possible to find a reduced-order or even static implementation.

Consider the following estimate

$$\Delta \hat{u} = (N(D,t) - \bar{N}(D,t))\Delta \hat{y}_f$$

(44)

of the control law (41) where $\Delta \hat{u}$ and $\Delta \hat{y}_f$ denote estimates for $\Delta u$ and $\Delta y_f$ respectively. For the dynamics of the estimation error $\Delta \hat{u} - \Delta u$ the following homogeneous differential equation can be assigned

$$\Delta(D)(\Delta \hat{u} - \Delta u) = 0$$

(45)

If $\Delta(D)$ is a stable polynomial matrix (i.e. $\det(\Delta(D))$ is a Hurwitz polynomial), the estimation error decays to zero. The dynamic output feedback controller realizing the error dynamics (45) is obtained by substituting (41) in the right hand side of

$$\Delta(D)\Delta \hat{u} = \Delta(D)\Delta u$$

(46)

yielding

$$\Delta(D)\Delta \hat{u} = \Delta(D)(N(D,t) - \bar{N}(D,t))\Delta y_f$$

(47)

Since the dynamic output feedback controller uses $\Delta u$ and $\Delta y$ as inputs, one has to set

$$\Delta(D)\Delta \hat{u} = \Delta(D)(N(D,t) - \bar{N}(D,t))\Delta y_f$$

$$\Delta(D)\Delta u = \Delta(D)(N(D,t) - \bar{N}(D,t))\Delta y_f$$

(48)

Substituting $\Delta u = N(D,t)\Delta y_f$ (see (28)) and $\Delta y = Z(D,t)\Delta y_f$ (see (29)) in (48) yields

$$\Delta(D)\Delta u = \Delta(D)(N(D,t) - \bar{N}(D,t))\Delta y_f$$

$$= Z_u(D,t)\Delta u + Z_y(D,t)\Delta y$$

$$= (Z_u(D,t)N(D,t) + \ldots + Z_y(D,t)\bar{Z}(D,t))\Delta y_f$$

(49)

From (49) the Diophantine equation

$$Z_u(D,t)N(D,t) + Z_y(D,t)\bar{Z}(D,t) =$$

$$\Delta(D)(N(D,t) - \bar{N}(D,t))$$

(50)

is deduced, which has to be solved in order to determine the unknown matrices $Z_u(D,t)$ and $Z_y(D,t)$. In (Limanond and Tsakalis, 2001) conditions for the existence of a solution of (50) are given, which can be used to find a general form of $Z_u(D,t)$ and $Z_y(D,t)$ consisting of polynomials in $D$ with unknown time varying coefficients. These coefficients are determined by a generally under-determined system of linear time varying equations, which is easily derived by inserting the general expressions for $Z_u(D,t)$ and $Z_y(D,t)$ into (50) and reordering subsequently. The resulting set of equations is only solvable, if the Sylvester matrix related to the pair $Z(D,t)$ and $N(D,t)$ has full rank (see (Limanond and Tsakalis, 2001)). As this can always be assured by suitable trajectory planning, it does not mean serious restrictions. Moreover, if the system of equations is very complex, no general symbolic solution may be found. In any case, however, sample values for the elements of $Z_u(D,t)$ and $Z_y(D,t)$ can be calculated numerically for any discrete points in time of interest. Remaining degrees of freedom may be used to simplify the solution or to achieve additional requirements of the controller (see also the example in Section 4). Accordingly, the dynamic output feedback controller resulting from (48) and (43) can be summarized as follows

$$\Delta(D)\Delta \hat{u} = Z_u(D,t)\Delta u + Z_y(D,t)\Delta y$$

(51)

$$u = u_d + \Delta \hat{u}$$

(52)

If the initial conditions of the system (1)–(2) are not significantly inconsistent with the starting point $y_{f,d}(0)$ of the reference trajectory and no disturbances are present, the error $\Delta \hat{u} - \Delta u$ will start converging to zero independently from the inputs of the feedback controller $\Delta u$ and $\Delta y$. As a result, when assuming that the dynamics chosen in (45) is sufficiently fast, the controller (51)–(52) stabilizes the tracking according to the differential equation (36). Even if disturbances must be taken into account, this conclusion remains valid as long as the caused errors $\Delta \hat{u} - \Delta u$ are small.

### 4. EXAMPLE

In the following the normalized third order ($n = 3$) state space representation of a uniaxial vehicle

$$\begin{align*}
\dot{x}_1 &= \frac{1}{2}(u_1 + u_2) \cos x_3 \\
\dot{x}_2 &= \frac{1}{2}(u_1 + u_2) \sin x_3 \\
\dot{x}_3 &= \frac{1}{2}(u_1 - u_2) \\
y &= [y_1, y_2]^T = [x_1, x_2]^T
\end{align*}$$

(53)

(54)

is considered, where the inputs $u_1$ and $u_2$ are the the left and right track velocity, the outputs $y_1$ and $y_2$ represent the position in a fixed Cartesian coordinate system and the state $x_3$ means the angle between vehicle velocity and $y_1$-axis. A
flat output $y_f$ is given by the physical output $y$ (see (Martin et al., 1997)), i.e.

$$y_f = [y_{f1}, y_{f2}]^T = y \quad (55)$$

As reference trajectory

$$y_{f,d} = [r \sin \frac{\omega}{T}, -r \cos \frac{\omega}{T}]^T \quad (56)$$

is assigned, which describes a circular movement with radius $r = 10$ at the constant speed $v_0 = 5$. In contrast to the assumptions in Section 2.1, the model (53) is not static feedback linearizable. This can easily be seen by evaluating relationship (5) to

$$u = \psi_v(y_{f1}, \ldots, y_{f1}^{(k_1)}, y_{f2}, \ldots, y_{f2}^{(k_2)}) = \psi_v(y_{f1}, \tilde{y}_{f1}, y_{f2}, \tilde{y}_{f2}) \quad (57)$$

from which

$$\kappa_1 + \kappa_2 = 2 + 2 > n = 3 \quad (58)$$

can be deduced. However, the problem can be solved by introducing the controller state

$$x_4 = \sqrt{\tilde{y}_{f1}^2 + \tilde{y}_{f2}^2} \quad (59)$$

with $\frac{1}{2}(u_1 + u_2) = x_4$ and the new inputs

$$v = [v_1, v_2]^T = [\dot{x}_4, \frac{1}{2}u_2]^T \quad (60)$$

resulting in the extended static feedback linearizable system described by

$$\begin{align*}
\dot{x}_1 &= x_4 \cos x_3 \\
\dot{x}_2 &= x_4 \sin x_3 \\
\dot{x}_3 &= x_4 - 2v_2 \\
\dot{x}_4 &= v_1 \\
\vec{y} &= [y_1, y_2, x_4]^T
\end{align*} \quad (61)$$

Note that the measurable controller state $x_4$ is included as additional output in (62). Analogously to (5) and (11), the new input $v$ can be expressed in terms of the flat output $y_f$ as

$$v = \psi_v(y_{f1}, \tilde{y}_{f1}, y_{f2}, \tilde{y}_{f2}) \quad (63)$$

and the feedforward controller for the extended system (61) is directly given as

$$v_d = \psi_v(y_{f1,d}, \tilde{y}_{f1,d}, y_{f2,d}, \tilde{y}_{f2,d}) \quad (64)$$

by inserting the reference trajectory (56) into (63).

The extended state representation (61) is converted into controller form by employing the state transformation

$$\begin{align*}
z &= [y_{f1}, \tilde{y}_{f1}, y_{f2}, \tilde{y}_{f2}]^T \\
z &= [x_1, x_4 \cos x_3, x_2, x_4 \sin x_3]^T
\end{align*} \quad (65) \quad (66)$$

(see (6)). Subsequently, the result (see (8)–(9)) is linearized about the reference trajectory $z_d$ given by

$$z_d = [y_{f1,d}, \tilde{y}_{f1,d}, y_{f2,d}, \tilde{y}_{f2,d}]^T \quad (67)$$

and $v_d$ (see (64)), which yields

$$\Delta z^* = \begin{bmatrix} 0 & -5 \cos \frac{\omega}{T} \sin \frac{\omega}{T} & 0 & -\frac{11}{2} \cos \frac{\omega}{T} \\
0 & \frac{1}{2} + 5 \cos \frac{\omega}{T} \sin \frac{\omega}{T} & 0 & 5 \cos \frac{\omega}{T} \sin \frac{\omega}{T} 
\end{bmatrix} \Delta z$$

$$+ \begin{bmatrix} \cos \frac{\omega}{T} & 10 \sin \frac{\omega}{T} \\
\sin \frac{\omega}{T} & -10 \cos \frac{\omega}{T} 
\end{bmatrix} \Delta T \quad (68)$$

$$\Delta \vec{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & \sin \frac{\omega}{T} 
\end{bmatrix} \Delta z \quad (69)$$

(see (17)) where $\Delta z^* = [\Delta z_2, \Delta z_4]^T$ according to (13), $\Delta v = v - v_d$ and $\Delta \vec{y} = \vec{y} - \vec{y}_d$. Using these results the polynomial matrices

$$N(D,t) = \begin{bmatrix} \cos \frac{t}{2} D^2 - \frac{1}{8} \sin \frac{t}{2} D \\
\sin \frac{t}{2} D^2 + \frac{11}{10} \cos \frac{t}{2} D \\
\frac{1}{10} \sin \frac{t}{2} D^2 + \frac{11}{10} \cos \frac{t}{2} D 
\end{bmatrix} \quad (70)$$

and

$$Z(D, t) = \begin{bmatrix} 1 & 0 \\
0 & 1 \\
\cos \frac{t}{2} D & \sin \frac{t}{2} D 
\end{bmatrix} \quad (71)$$

determining the differential operator representation (28) and (29) can be calculated by means of (26) and (27). The dynamics of the tracking error $\Delta y_f = y_f - y_{f,d}$ is specified by

$$\tilde{N}(D,t) = \Gamma_{\tilde{y}}[N(D,t)] \text{diag}(D^2 + 2D + 1, D^2 + 2D + 1) \quad (72)$$

(see 42) and the dynamics of the error $\Delta \dot{v} - \Delta v$ is assigned by

$$\Delta \tilde{N}(D) = \begin{bmatrix} D^{10} & 0 \\
0 & D^{10} 
\end{bmatrix} \quad (73)$$

Using the conditions established in (Limanond and Tsakalis, 2001) it can be shown that the Diophantine equation (50) can be fulfilled by polynomial matrices $Z_\epsilon(D,t)$ and $Z_{\vec{y}}(D,t)$ with $\text{deg}(Z_\epsilon) = 0$ and $\text{deg}(Z_{\vec{y}}) = 1$. Thus, the solution can be written in the general form

$$Z_\epsilon(D,t) = \begin{bmatrix} \tilde{z}_{11}(t) & \tilde{z}_{12}(t) \\
\tilde{z}_{21}(t) & \tilde{z}_{22}(t) 
\end{bmatrix} \quad (74)$$

$$Z_{\vec{y}}(D,t) = \begin{bmatrix} \tilde{z}_{11}(t)D + \tilde{z}_{12}(t) \quad \tilde{z}_{21}(t)D + \tilde{z}_{22}(t) \\
\tilde{z}_{11}(t)D + \tilde{z}_{12}(t) \quad \tilde{z}_{21}(t)D + \tilde{z}_{22}(t) 
\end{bmatrix} \quad (75)$$

Note that the first-order terms in the last column of $Z_{\vec{y}}(D,t)$ are omitted, since $\tilde{z}_1 = \dot{x}_4 = v_1$ (see (60)) meaning that without loss of generality these coefficients can be included in the zero-order terms in the first column of $Z_\epsilon(D,t)$. Inserting the general expressions (74)–(75) into (50) leads to a system of 12 independent linear time varying equations for the 14 unknown coefficients in $Z_\epsilon(D,t)$ and $Z_{\vec{y}}(D,t)$, which can be solved with the assistance of the computer algebra system MAPLE. The two resulting degrees of freedom in the solution are determined by the condition that all coefficients in $Z_\epsilon(D,t)$ and $Z_{\vec{y}}(D,t)$ must
nonlinear systems has been developed. The feedback controller combined with a nonlinear controller achieves time invariant tracking error in this contribution a systematic design procedure using the linear approach. Thus, stabilized tracking is achieved by the inputs large errors and disturbances the simulated dynamic behavior did not worsen significantly when the order of the considered dynamics in the vicinity of the reference trajectory. The applicability of the proposed scheme remains bounded for all times $t$. Hence, the dynamic output feedback controller (51) is specified completely. One possible realization of the controller (51) is obtained by introducing the controller states $\Delta \xi = [\Delta \xi_1, \Delta \xi_2]^T$ according to

$$\Delta \xi_1 = \Delta \dot{v}_1 - z_{1,1}^1(t) \Delta \bar{y}_1 - z_{1,2}^1(t) \Delta \bar{y}_2$$

$$\Delta \xi_2 = \Delta \dot{v}_2 - z_{1,2}^1(t) \Delta \bar{y}_1 - z_{1,2}^2(t) \Delta \bar{y}_2$$

(76)

(77)

which results in the state space representation

$$\Delta \dot{\xi} = \begin{bmatrix} -10 & 0 \\ 0 & -10 \end{bmatrix} \Delta \xi + \begin{bmatrix} -2 & -5 \\ -\frac{15}{2} & -2 \end{bmatrix} \Delta v +$$

$$\begin{bmatrix} \cos \frac{t}{10} + \sin \frac{t}{10} & -\cos \frac{t}{10} - \sin \frac{t}{10} \\ 20 \sin \frac{t}{10} + \cos \frac{t}{10} & -20 \cos \frac{t}{10} - \sin \frac{t}{10} \end{bmatrix} \Delta \bar{y}$$

(78)

$$\Delta \dot{v} = \Delta \xi + \begin{bmatrix} -5 \sin \frac{t}{10} + 5 \cos \frac{t}{10} \\ -\frac{15}{2} \sin \frac{t}{10} - \frac{15}{2} \cos \frac{t}{10} \end{bmatrix} \Delta \bar{y}$$

(79)

Thus, stabilized tracking is achieved by the inputs (see (52))

$$v_1 = v_{1,d} + \Delta \dot{v}_1$$

$$v_2 = v_{2,d} + \Delta \dot{v}_2$$

(80)

(81)

where $v_{1,d}$ and $v_{2,d}$ are determined by the nonlinear feedforward controller (64). Note that the overall order of the so defined controller is three, since not only a realization of the state space model (78)–(79) must be provided but also an implementation of the system extension (59)–(60). The presented feedback design was simulated applying MATLAB/SIMULINK and the results were compared to the well-established flatness-based approach using a dynamic nonlinear state feedback controller combined with a nonlinear tracking observer with a linear time varying observer gain (see e.g. (Fliess and Rudolph, 1996) for details). Although the order of the considered nonlinear controller was four, i.e. by one higher than the corresponding order of the linear design, both offered a very similar performance assuming small errors in the initial state, which is shown in Figure 1 for the initial state errors $x_1(0) - x_{1,d}(0) = -0.05 r$, $x_2(0) - x_{2,d}(0) = 0.05 r$ and $x_3(0) - x_{3,d}(0) = 0.05 t$. Moreover, even for relatively large errors and disturbances the simulated dynamic behavior did not worsen significantly when using the linear approach.

5. CONCLUSIONS

In this contribution a systematic design procedure for linear dynamic output feedback controllers for nonlinear flat systems has been developed. The controller achieves time invariant tracking error dynamics in the vicinity of the reference trajectory. The applicability of the proposed scheme has been shown for a uniaxial vehicle model. Even more general linear time varying system descriptions than (28)–(29) could be used for the controller design, see e.g. (Levine and Nguyen, 2003).

REFERENCES


