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A
Stability Analysis

In this section, the proof of stability and convergence analysis of the proposed controllers will be discussed by using the Lyapunov stability theory [2]. Consider the system described by the following ordinary differential equation $\dot{\mathbf{x}} = f(\mathbf{x})$, where $\mathbf{x} \in \mathbb{R}^n$ is the error state. By setting $f(\mathbf{x}) = 0$ the equilibrium state is given by $\mathbf{x} = 0$. A continuous scalar function $V(\mathbf{x})$ of the system state, with continuous first time-derivative, is called a Lyapunov function if the following properties hold:

$$
\begin{aligned}
&(1) \quad V(\mathbf{x}) > 0\,, \quad \forall \mathbf{x} \neq 0\,,\\
&(2) \quad V(\mathbf{x}) = 0\,, \quad \mathbf{x} = 0\,.\\
&(3) \quad \dot{V}(\mathbf{x}) < 0\,, \quad \forall \mathbf{x} \neq 0\,,\\
&(4) \quad V(\mathbf{x}) \to \infty\,, \quad ||\mathbf{x}|| \to 0\,.
\end{aligned}
\tag{A-1}
$$

From the Lyapunov stability paradigm we must select a proper Lyapunov candidate function $V(\mathbf{x})$ in order to analyze the stability of the error system. The existence of such a function ensures the global asymptotic stability property of the equilibrium point $\mathbf{x} = 0$.

A.1
Proof of Theorem 2.1

In order to proof the theorem and consequently the stability of the controller proposed in (2-12), the Lyapunov stability theory is used, in which it is necessary to find a Lyapunov candidate function which satisfies the first condition in (A-1), and that its time derivative is always negative definite or semidefinite negative. Considering the following Lyapunov candidate function:

$$2V(e_x, e_y) = \left(e_x^2 + e_y^2\right) \ . \tag{A-2}$$

Now in order to proof that the Lyapunov function V follows the second condition in (A-1) we compute its time derivative as follows:

$$\dot{V}(e_x, e_y) = \left(e_x \dot{e}_x + e_y \dot{e}_y\right) \ . \tag{A-3}$$

Taking into consideration the kinematic model of the TMR (2-3) and the error position in (2-11), we substitute the time derivatives $\dot{e_x}$ and $\dot{e_y}$, as follows:

$$\dot{V}(e_x, e_y) = e_x\,(v\cos\theta + d\omega\sin\theta) + e_y\,(v\sin\theta - d\omega\cos\theta)\ .$$

Rewritting the above equation, we obtain:

$$\dot{V}(e_x, e_y) = v\,(e_x\cos\theta + e_y\sin\theta) + d\omega\,(e_x\sin\theta - e_y\cos\theta)\ .$$

Replacing the slippage factor d from (2-8) yields:

$$\dot{V}(e_x, e_y) = v\,(e_x\cos\theta + e_y\sin\theta) + k\omega^3\,(e_x\sin\theta - e_y\cos\theta)\ .$$

Finally, considering the control laws defined in (2-12), we have:

$$\dot{V}(e_x, e_y) = -k_1\,(e_x\cos\theta + e_y\sin\theta)^2 - kk_2^3\,(e_x\sin\theta - e_y\cos\theta)^4\ . \tag{A-4}$$

Now, we can observe that the time-derivative of V obtained in (A-4) is negative semi-definite at the origin, $\dot{V} \leq 0$. However, $\dot{V}$ does not satisfy the condition 3 defined in (A-1). This indicates that V tends to a limit value, $V \in \mathcal{L}_\infty$, and also that the position error (e_x, e_y) is bounded in norm, that is, $e_x, e_y \in \mathcal{L}_\infty$ It is straightforward to verify that $\ddot{V}$ is also bounded, $\ddot{V} \in \mathcal{L}_\infty$, and thus $\dot{V}$ is uniformly continuous. Indeed, we can show that $\ddot{V}$ depends on the combination of bounded trigonometric functions and double-angle formulae. Then, the Barbalat's lemma implies that $\dot{V}$ tends to zero. Hence, as a consequence, we conclude that:

$$\lim_{t\to\infty}(e_x\cos\theta + e_y\sin\theta) = 0\,, \qquad \lim_{t\to\infty}(e_x\sin\theta - e_y\cos\theta) = 0\,, \tag{A-5}$$

that is, the projection of the Cartesian error vector (e_x, e_y) on the sagittal axis of the TMR tends to vanish. Therefore, the Cartesian error tends to zero when the TMR is moved from any initial configuration to any desired configuration.

A.2
Proof of Theorem 2.2

In this section the proof of the Theorem 2.2 is performed, as a first step the linearization of the system (2-19) is determined. In order to linearize the system next considerations are assumed:

$$\cos\alpha = 1,\ \sin\alpha = \alpha$$
$$\cos\beta = 1,\ \sin\beta = \beta$$
$$\rho\beta = 0,\ \alpha\beta = 0$$

Now, it is necessary redefine the kinematic model in equation 2-19, taking account the control laws defined in equation 2-20, starting with $\dot{\rho}$:

$$\begin{aligned}\dot{\rho} &= k_\rho \rho \cos\alpha - (k_\alpha \alpha + k_\beta \beta)\, d \sin\alpha \\ &= k_\rho \rho - (k_\alpha \alpha + k_\beta \beta)\, d\alpha\ ,\end{aligned}$$

reducing:

$$\dot{\rho} = k_\rho \rho \tag{A-6}$$

Next we find, $\dot{\alpha}$:

$$\begin{aligned}\dot{\alpha} &= -\left(k_\alpha \alpha + k_\beta \beta\right) - \frac{k_\rho \rho \sin\alpha}{\rho} - \frac{d\left(k_\alpha \alpha + k_\beta \beta\right)\cos\alpha}{\rho} \\ &= -\left(k_\alpha \alpha + k_\beta \beta\right) - k_\rho \alpha - \frac{d\left(k_\alpha \alpha + k_\beta \beta\right)}{\rho}\ ,\end{aligned}$$

simplifying:

$$\dot{\alpha} = -\alpha\left(k_\alpha - k_\rho\right) - k_\beta \beta \tag{A-7}$$

Finally we find $\dot{\beta}$:

$$\begin{aligned}\dot{\beta} &= \frac{k_\rho \rho \sin\alpha}{\rho} + \frac{d\left(k_\alpha \alpha + k_\beta \beta\right)\cos\alpha}{\rho} \\ &= k_\rho \alpha + \frac{d\left(k_\alpha \alpha + k_\beta \beta\right)}{\rho}\ ,\end{aligned}$$

reducing:

$$\dot{\beta} = k_\rho \alpha \tag{A-8}$$

Now, we can establish a linear system in the form of state space representation as $\dot{\mathbf{x}} = A\mathbf{x}$ as follows:

$$\begin{bmatrix}\dot{\rho} \\ \dot{\alpha} \\ \dot{\beta}\end{bmatrix} = \begin{bmatrix}-k_\rho & 0 & 0 \\ 0 & -(k_\alpha - k_\rho) & -k_\beta \\ 0 & k_\rho & 0\end{bmatrix}\begin{bmatrix}\rho \\ \alpha \\ \beta\end{bmatrix}. \tag{A-9}$$

Thus, in order to analyze the internal stability of the system, we need to find the eigenvalues λ for the matrix A and ensure that the real part of all eigenvalues is negative, $\mathrm{Re}\{\lambda_i(A)\} < 0$ for $i = 1, 2, 3$. Next, the characteristic polynomial $\Delta(\lambda) = \det(\lambda I - A)$ is given by:

$$\Delta(\lambda) = (\lambda + k_\rho)\left[\lambda^2 + \lambda(k_\alpha - k_\rho) - k_\rho k_\beta\right]. \tag{A-10}$$

Analyzing the characteristic polynomial $\Delta(\lambda)$ and finding its roots, we obtain:

$$\lambda_1 = -k_\rho\,, \qquad \lambda_2 = k_\beta\,, \qquad \lambda_3 = -(k_\alpha - k_\rho)\,. \tag{A-11}$$

Now, in order to satisfy the conditions for stability established by the Routh-Hurwitz criteria we have:

$$k_\rho > 0\,, \qquad k_\beta < 0\,, \qquad k_\alpha - k_\rho > 0\,, \tag{A-12}$$

which are the same condition defined by the Theorem 2.2.

A.3 Proof of Theorem 3.10

In order to proof the theorem, the Lyapunov stability theory is used, considering the next Lyapunov Function candidate:

$$V = \frac{1}{2}\left(z_1^2 + z_2^2\right)\ , \tag{A-13}$$

Deriving V respect time along to the trajectory system 3-20

$$\dot{V} = z_1 u_1 + z_2 u_2\ , \tag{A-14}$$

Substituting (3-26) into (A-14):

$$\begin{aligned}\dot{V} &= -z_1^2 - \alpha z_1 z_2 sgn(\sigma) - z_2^2 + \alpha z_1 z_2 sgn(\sigma)\\ &= -\left(z_1^2 + z_2^2\right)\\ &= -2V \le 0\end{aligned} \tag{A-15}$$

From (A-15) can be concluded that the states z_1 and z_2 converge to $(0,\,0,\,z_3)$. Then it is necessary to warranty the sliding condition $\sigma\dot{\sigma}$, first we find $\dot{\sigma}$:

$$\begin{aligned}\dot{\sigma} &= 2\dot{z}_3 - \dot{z}_1 z_2 - z_1\dot{z}_2\\ &= 2\left(z_2 v_1 + d v_1\right) - z_1 v_2 - z_2 v_1\\ &= z_2 v_1 - z_1 v_2 + d v_1\\ &= -z_2 z_1 - \alpha z_2^2 sgn(\sigma) + z_2 z_1 - \alpha z_1^2 sgn(\sigma) + d v_1\\ &= -\alpha\left(z_1^2 + z_2^2\right) sgn(\sigma) + d v_1\end{aligned} \tag{A-16}$$

Then we calculate the sliding condition $\dot{\sigma}\sigma$ as follows:

$$\begin{aligned}\dot{\sigma}\sigma &= -\alpha V \sigma sgn(\sigma) + \sigma v_1\\ &= -\alpha V \sigma sgn(\sigma) + \sigma\alpha\left(-z_1 - \alpha z_2 sgn(\sigma)\right)\\ &= -\alpha V \sigma sgn(\sigma) - \sigma d z_1 - \alpha z_2 \alpha\sigma sgn(\sigma)\\ &= -\alpha V \sigma sgn(\sigma) - \alpha z_2 \alpha \sigma sgn(\sigma) - \sigma d z_1\end{aligned} \tag{A-17}$$

Since from (A-15) we can affirm that $\lim_{t\to\infty} z_1 = 0$ and $\lim_{t\to\infty} z_2 = 0$, is it possible to ensure that $\dot{\sigma}\sigma = -\alpha V \sigma sgn(\sigma) < -\beta|\sigma|$, for $\beta > 0$ that is $\sigma = 0$ guaranteeing the convergence of z_3 to zero , since $2z_3 = z_1 z_2$.

From (A-15), (A-16) and (A-17) and V is a positive definite function, it is well known that absolute value of σ decrease and converge to zero in finite time if $V(0) = |\sigma(0)|$ and $\dot{V} = \dot{\sigma} sign(\sigma)$, then:

$$\int_0^\infty \dot{V}(\tau)d\tau > \int_0^\infty \dot{\sigma}(\tau) sign(\sigma(\tau))d\tau \tag{A-18}$$

Substituting (A-16) in (A-18), implies:

$$V(0) < 2\alpha \int_0^\infty V(\tau)d\tau$$

As is known $V(0) > |\sigma(0)|$, we have:

$$2\alpha \int_0^\infty V(\tau)d\tau > |\sigma(0)| \tag{A-19}$$

Then, according (A-17) and if equation (A-19) is satisfied, all the trajectories of the system converge to a slides surface $\sigma = 0$ and consequently $z_1 z_2 = 2z_3$ guaranteeing the convergence of z_3 to zero.

Finally, substituting the solution of the equation (A-18)

$$V(t) = V(0)e^{-2t} = \frac{1}{2}(z_1(0)^2 + z_2(0)^2)e^{-2t}$$

in equation (A-19) and integrating with respect to time, obtaining a condition for the system be stabilized, that is:

$$\frac{\alpha}{2}\left(z_1(0)^2 + z_2(0)^2\right) > |\sigma(0)| \tag{A-20}$$

It is good to remark if the condition (A-20) were an inequality, σ converges to zero in finite time (asymptotic stability). Then, we conclude that $\sigma \to 0$ the initial conditions have to satisfied the equation (A-17), guaranteeing the local stability of the origin.

Remark 2 *If the initial condition is not in the region Υ, can be used any control law to drive the states to the region defined by equation* (3-24)*. Using a constant control law $[v_1\, v_2]^\mathsf{T} = [c_1\ c_2]^\mathsf{T}$ the states drives to the region Υ. Then a global feedback control law can be:*

$$[v_1\ u_2]^\mathsf{T} = \begin{cases} [c_1\ c_2]^\mathsf{T} & , [z_1\ z_2\ z_3]^\mathsf{T} \notin \Upsilon \\ \text{(3-26)} & , [z_1\ z_2\ z_3]^\mathsf{T} \in \Upsilon. \end{cases} \tag{A-21}$$

B
Chained Form for Unicycle Case

In this appendix, we present the formulation of the chained form system for the Unicycle Mobile robot, this mobile robot is widely used as its transformation into chain system but it is a lack of information about how the authors find out the transformation, this appendix will explain step by step the generation of the chained form system for this model.

In order to start the transformation is necessary define its Kinematic Model are were defined in equation (B-1).

$$\begin{aligned} \dot{q} &= g_1 v + g_2 \omega \\ \dot{q} &= \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} v + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \omega \ , \end{aligned} \tag{B-1}$$

Remark 3 *It is worth to remark that the assignment of g_1 and g_2 plays an important rule in the chained form system, because they have effects in the chained form system making it non-viable or viable.*

In the case of chained system for Unicycle model there are two possible choices:

1. $g_1 = [\cos\theta \ \ \sin\theta \ \ 0]^T$ and $g_2 = [0 \ \ 0 \ \ 1]^T$
2. $g_1 = [0 \ \ 0 \ \ 1]^T$ and $g_2 = [\cos\theta \ \ \sin\theta \ \ 0]^T$

For the first choice we have verified that the chained system formulation is non-viable, because in the formulation of the **Step I** it is showed that the generating distributions $(\Delta_1, \Delta_2, \Delta_3)$ are not involutive. Now it is clear according the equation B-1 the second choice is chosen, next we will continue with the formulation.

Step I: Defining the distributions distributions:

$$\begin{aligned} \Delta_0 &= span\,\{g_1\,,\ g_2\,,\ ad_{g_1}g_2\} \\ \Delta_1 &= span\,\{g_2\,,\ ad_{g_1}g_2\} \qquad , \\ \Delta_2 &= span\,\{g_2\} \end{aligned}$$

Finding $ad_{g_1}g_2$:

$$ad_{g_1}g_2 = [\,g_1, g_2\,] = \frac{\partial g_2}{\partial q}g_1(q) - \frac{\partial g_1}{\partial q}g_2(q)$$

$$[\,g_1, g_2\,] = \begin{bmatrix} 0 & 0 & -\sin\theta \\ 0 & 0 & \cos\theta \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} = \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix},$$

Now, building the span distribution:

$$\Delta_1 = span\left\{ \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix}, \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} \right\}$$
$$\Delta_2 = span\left\{ \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix}, \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} \right\}$$
$$\Delta_3 = span\left\{ \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} \right\},$$

It is important to check that the distribution is involutive, it is clear that the Δ_1 and Δ_3 are involutive, now we have to verify with Δ_2. For this objective we need to check if $[ad_{g_1}\ , \ g_2] \in \Delta_2$, finding $[ad_{g_1}\ , g_2]$:

$$[\,g_2, [ad_{g_1}\ ,\ g_2]\,] = \begin{bmatrix} 0 & 0 & -\cos\theta \\ 0 & 0 & -\sin\theta \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} - \begin{bmatrix} 0 & 0 & -\sin\theta \\ 0 & 0 & \cos\theta \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},$$

The result vector is in Δ_2.

Step II: The functions h_1 and h_2 are required:

- The function h_1 is chosen as $h_1 = \theta$, now the dh_1 is computed:

$$dh_1 = \frac{\partial h_1}{\partial q} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix},$$

Now we verify each condition :

  - Condition $dh_1 \cdot \Delta_1 = 0$ for $\Delta_1 = \{g_2\}$

$$\begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} = 0 \ ,$$

– Condition $dh_1 \cdot \Delta_1 = 0$ for $\Delta_1 = \{ad_{g_1} g_2\}$

$$\begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} = 0 \ ,$$

– Condition $dh_1 \cdot g_1 = 1$ is verified:

$$\begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = 1 \ ,$$

- The function h_2 is chosen as: $h_2 = x\sin\theta - y\cos\theta$, now finding dh_2:

$$dh_2 = \frac{\partial h_2}{\partial q} = \begin{bmatrix} \sin\theta & -\cos\theta & (x\cos\theta + y\sin\theta) \end{bmatrix}$$

We verify that the condition $dh_2 \cdot \Delta_2 = 0$:

$$\begin{bmatrix} \sin\theta & -\cos\theta & (x\cos\theta + y\sin\theta) \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} = 0 \ ,$$

Step III: Mapping $\phi : x \to z$ by a transformation given by:

$$\begin{aligned} z_1 &= h_1 & v_1 &:= u_1 \\ z_2 &= L_{g_1} h_2 & v_2 &:= \left(L_{g_1}^2 h_2\right) u_1 + \left(L_{g_2} L_{g_1} h_2\right) u_2 \ , \\ z_3 &= h_2 \end{aligned}$$

Having the function h_1 we can see that $z_1 = h_1 = \theta$, next we will calculate

$z_2 = L_{g_1} h_2$ as follows:

$$
\begin{aligned}
z_2 = L_{g_1} h_2 &= \frac{\partial h_2}{\partial q} \cdot g_1 \\
&= \begin{bmatrix} \sin\theta & -\cos\theta & (x\cos\theta + y\sin\theta) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\
&= x\cos\theta + y\sin\theta \ ,
\end{aligned}
$$

Having the expression for h_2 , we have $z_3 = h_2 = x\cos\theta - y\cos\theta$, now we look for the expression $v_2 = \left(L_{g_1}^2 h_2\right)$:

$$
\begin{aligned}
\left(L_{g_1}\left(L_{g_1} h_2\right)\right) &= \left(L_{g_1}\left(x\cos\theta + y\sin\theta\right)\right) \\
&= \begin{bmatrix} \cos\theta & \sin\theta & (-x\sin\theta + y\cos\theta) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\
&= -x\sin\theta + y\cos\theta \ ,
\end{aligned}
$$

And we find the other part for the expression of v_2:

$$
\begin{aligned}
\left(L_{g_2}\left(L_{g_1} h_2\right)\right) &= \left(L_{g_2}\left(x\cos\theta + y\sin\theta\right)\right) \\
&= \begin{bmatrix} \cos\theta & \sin\theta & (-x\sin\theta + y\cos\theta) \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \\ 0 \end{bmatrix} \\
&= 1 \ ,
\end{aligned}
$$

The final expression for the mapping is :

$$
\begin{aligned}
z_1 &= \theta & v_1 &= \omega \\
z_2 &= x\cos\theta + y\cos\theta & v_2 &= \left(-x\sin\theta + y\sin\theta\right)\omega + v \ , \\
z_3 &= x\sin\theta - y\cos\theta
\end{aligned}
\tag{B-2}
$$

In order to find the chained form, we derive the states z_1, z_2, z_3 in function of the time (taking into consideration the kinematic model in equation) B-1:

$$
\begin{aligned}
\dot{z}_1 &= \omega \\
\dot{z}_2 &= \left(-x\sin\theta + y\sin\theta\right)\omega + v \ , \\
\dot{z}_3 &= \omega(x\cos\theta + y\cos\theta)
\end{aligned}
\tag{B-3}
$$

This yields to the chained form system:

$$\begin{aligned} \dot{z}_1 &= v_1 \\ \dot{z}_2 &= v_2 \quad , \\ \dot{z}_3 &= z_2 v_1 \end{aligned} \tag{B-4}$$

It is also clear to see that there is a transformation among the input signal control in the chained system and the input control in the Kinematic model,

$$\begin{aligned} &v_1 = \omega \\ &v_2 = (-z_3)\,\omega + v \end{aligned} \tag{B-5}$$

Then going to the matrix form:

$$v = Tu = \begin{bmatrix} 0 & 1 \\ 1 & -z_3 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{B-6}$$

As can be seen we can express the input controls for the unicycle u in function of T and v as follows:

$$\begin{gathered} u = T^{-1} v \\ \begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & -z_3 \end{bmatrix}^{-1} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \end{gathered} \tag{B-7}$$