A Car-like Mobile Manipulator with an n-link Prismatic Arm

Ravinesh Chand †,*, Sandeep A. Kumar ‡, Ronal P. Chand † and Shabnam Reddy‡

***Abstract*—In this research, the Lyapunov based Control Scheme (LbCS) is used to solve the motion planning and control problem of a car-like mobile robot with a long extendible prismatic arm comprising $n \in \mathbb{N}$ links. The prismatic arm consists of a base revolute joint and $n \in \mathbb{N}$ translational joints, and is mounted on the wheeled car-like mobile platform. The kinematic model of the manipulator is developed, and velocity based algorithms are utilized to firstly, move the car-like base from an initial position to its pseudo-target and secondly, maneuver the end-effector to its designated target, taking into account the restrictions and limitations of the prismatic links and the steering control laws of the system. Computer simulations are presented to illustrate the effectiveness of the proposed control laws.**

***Index Terms*—prismatic, n-link robotic arm, mobile manipulator, motion planning, velocity controllers**

I. Introduction

Robots are highly valued in industrial applications for several characteristics such as reliability, repeatability, precision, and the ability to operate in dangerous working environments [1]–[3]. Recently, mobile robotics has emerged as one of the fastest expanding fields of scientific research, playing a vital role in improving human livelihood [4]–[6]. A mobile manipulator is a mechanical system containing an articulated robotic arm mounted on a mobile platform and can provide specific maneuverability that anchored manipulators cannot [7], [8]. According to Sharma et al. [9], a robotic arm consists of rigid links interconnected by joints such as revolute or prismatic, with the end of the arm connected to an end-effector.

Mobile manipulators can be used for multiple purposes in real-life applications such as transportation [10], [11], pick-and-place [12], and labor intensive work [10]. Due to the possibility of a wide array of applications for the robotic mechanical systems, motion planning and control continuously provide challenges for researchers. These challenges faced in controlling the motion of mobile manipulators are in the complexity of the control algorithms, intensive computations and the difficulty of simulations [7], [13].

The Lyapunov-based Control Scheme (LbCS), adopted from a classical approach known as Artificial Potential Field method, is commonly used in robotics research for motion planning and control of numerous robotic systems [14]–[20]. Sharma et al. in 2012 [7] developed a set of control laws based on LbCS for autonomous navigation of a revolute n-link car-like manipulator. In addition, Sharma et al. in 2017 [2] designed a decentralized continuous control laws that successfully navigated the multiple doubly nonholonomic mobile revolute manipulators to their goals in a constrained and bounded environment, intrinsically guaranteeing the stability of the robotic system.

A wheeled car-like robot with a prismatic arm, which has the potential to play an important practical role in transport, logistics, and distribution, is considered in this research. Wheeled robots are cost-effective and easier to design, build and program compared to the robots proposed in studies such as [21], [22], which use treads or legs. In addition, the main advantage of such robots is that they do not pose any risks in terms of balance issues, maneuverability, and control, since the robot is constantly in contact with a surface [23]. The mobile manipulator considered in this research is more stable than the mobile robots utilised in [21], [22], because the center of gravity is located inside the rectangle formed by the four wheels of the car-like platform.

This research aims to develop the velocity controllers of an n-link prismatic robotic arm mounted on a car-like mobile manipulator, which navigates to its target to perform assigned tasks. This method can offer valuable contributions in real-life applications such as health care, manufacturing, assembly line production, and industrial tasks involving picking objects and placing them over long distances. Notably, the use of such car-like manipulators in health care can help avoid cross-infection of COVID-19 and lessen the workload of the hard-pressed medical workers.

The main contributions of this paper are (1) motion planning of a car-like mobile manipulator with an n-link prismatic arm that can accomplish tasks within a workspace, and (2) a two step target attraction technique for the car-like vehicle and the end-effector of the robotic arm.

In Section 2, the car-like mobile manipulator with an n-link prismatic robotic arm is presented. Section 3 discusses the motion planning and control problem that this paper will address. In Section 4, the velocity controllers are derived from a Lyapunov function. The stability analysis of the car-like system is given in Section 5. Then, in Section 6, the simulation results are presented, followed by conclusion and future work in Section 7.

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II. The mobile manipulator model

This research considers a mobile manipulator consisting of an articulated n-link arm with prismatic joints fixed on a rotatable base mounted on a rear wheel driven car-like mobile platform in the z_1z_2-plane as shown in Figure 1. The base contains a revolute joint, thus can rotate through 360^o along its principal axis. The articulated arm consists of n rigid links, which are connected via prismatic joints, and the n^{th} link has an end-effector. All the links of the arm are prismatic except the first one, which is revolute. With reference to Figure 1,

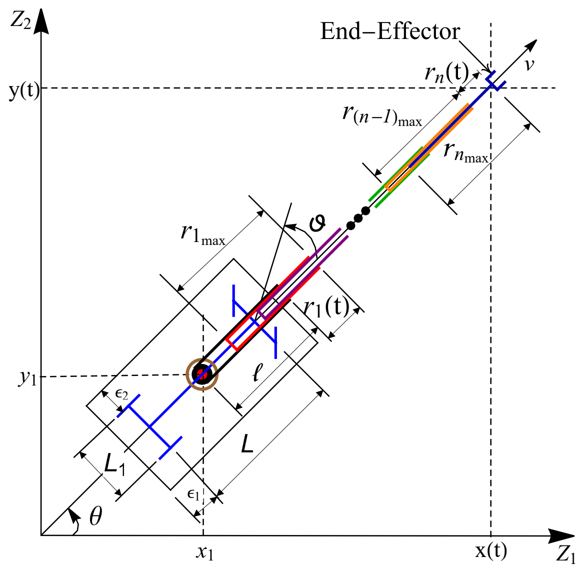

Fig. 1. Schematic representation of a car-like manipulator with front wheel steering and steering angle ϑ.

the following assumptions are made:

i. the center of the car-like mobile manipulator is positioned at $\boldsymbol{\kappa} = (x_1(t), y_1(t))$ and its orientation with respect to the z_1 axis is $\theta(t)$;
ii. the rotatable base of the robotic arm is anchored at $(x_1(t), y_1(t))$;
iii. the revolute link has a fixed length l;
iv. the k^{th} prismatic link has a maximum length r_{kmax} where $\{k = 1, 2, 3, \ldots, n\}$ and $r_k(t)$ is the extracted length of the k^{th} prismatic link;
v. the robotic arm has an angular position $\phi(t)$ at time t measured counterclockwise from the longitudinal axis of the car-like manipulator; and
vi. the coordinates of the end-effector, suppressing t, is (x, y) and given as:

$$x = x_1 + \left(l + \sum_{k=1}^{n} r_k\right) \cos(\theta + \phi),$$
$$y = y_1 + \left(l + \sum_{k=1}^{n} r_k\right) \sin(\theta + \phi). \tag{1}$$

Hence, the kinematic model of the car-like mobile manipulator with an n-link prismatic arm, upon suppressing t, is derived as follows:

$$\left.\begin{aligned}
\dot{x}_1 &= \nu \cos\theta - \tfrac{L}{2}\varpi \sin\theta, \\
\dot{y}_1 &= \nu \sin\theta + \tfrac{L}{2}\varpi \cos\theta, \\
\dot{x} &= \dot{x}_1 + \cos\phi \sum_{k=1}^{n} v_k - \omega y, \\
\dot{y} &= \dot{y}_1 + \sin\phi \sum_{k=1}^{n} v_k + \omega x, \\
\dot{\theta} &= \varpi, \\
\dot{\phi} &= \omega, \\
\dot{r}_k &= v_k.
\end{aligned}\right\} \tag{2}$$

The distance between the two axles of the car-like vehicle is denoted as L, the length of each axle is denoted as L_1, while $\epsilon_1 > 0$ and $\epsilon_2 > 0$ are the safety parameters of the car-like manipulator. The no-slip and no lateral movement conditions give rise to the mobile platform's non-holonomic constraints since the velocities perpendicular to the wheels are zero [2], [7]:

$$\dot{x}_{1_R} \sin\theta - \dot{y}_{1_R} \cos\theta = 0,$$
$$\dot{x}_{1_F} \sin(\theta + \vartheta) - \dot{y}_{1_F} \cos(\theta + \vartheta) = 0,$$

where $(\dot{x}_{1_F}, \dot{y}_{1_F})$ and $(\dot{x}_{1_R}, \dot{y}_{1_R})$ are the front and rear wheel velocities respectively. Furthermore, the position of the end-effector of the n-link prismatic robotic arm at $t \geq 0$ is denoted as $\boldsymbol{x} = (x(t), y(t))$. The angular and translational velocities of the car-like manipulator are given as $\theta'(t) = \varpi(t)$ and $\nu(t)$, respectively. At $t \geq 0$, the instantaneous translational velocity of the car-like manipulator is given as $(u_1(t), u_2(t)) := (x_1'(t), y_1'(t))$. The angular velocity and the translational velocity of the k^{th} prismatic link for $\{k = 1, 2, 3, \ldots, n\}$ are given by $\phi'(t) = \omega(t)$ and $r_k'(t) = v_k(t)$, respectively. Let $\boldsymbol{x}_0 = (x_0, y_0)$. The initial condition at $t_0 \geq 0$ are as $x_0 := x(t_0)$, $y_0 := y(t_0)$, $\theta_0 := \theta(t_0)$, $\phi_0 := \phi(t_0)$, $r_{k_0} := r_k(t_0)$. Suppressing t, the state vector of the system is given by $\mathbf{x} := (x_1, y_1, \theta, \phi, r_1, r_2, ..., r_n) \in \mathbb{R}^{n+3}$ and $\mathbf{x}_0 := \mathbf{x}(t_0) := (x_{1_0}, y_{1_0}, \theta_0, \phi_0, r_{1_0}, r_{2_0}, ..., r_{n_0}) \in \mathbb{R}^{n+3}$.

The state feedback law of the instantaneous velocity (u_1, u_2, ω, v_k) is given as:

$$\begin{aligned}
u_1(t) &:= -\psi p(\mathbf{x}(t)), \\
u_2(t) &:= -\rho q(\mathbf{x}(t)), \\
\omega(t) &:= -\alpha f(\mathbf{x}(t)), \\
v_k(t) &:= -\beta_k g_k(\mathbf{x}(t)),
\end{aligned}$$

where $k \in \{1, 2, 3, ..., n\}$, for some positive scalars $\psi, \rho, \alpha, \beta_k$, and some functions $p(\mathbf{x}(t)), q(\mathbf{x}(t)), f(\mathbf{x}(t))$ and $g_k(\mathbf{x}(t))$ to be constructed later, and if we define $\mathbf{G}(\mathbf{x}) := (-\psi p(\mathbf{x}), -\rho q(\mathbf{x}), -\alpha f(\mathbf{x}), -\beta_1 g_1(\mathbf{x}), -\beta_2 g_2(\mathbf{x}), ..., - \beta_n g(\mathrm{x})) \in \mathbb{R}^{n+1}$, then the system shown in Figure 1 is represented by

$$\dot{\mathbf{x}} = \mathbf{G}(\mathbf{x}), \quad \mathbf{x}(t_0) = \mathbf{x}_0. \tag{3}$$

III. MOTION PLANNING AND CONTROL

The Lyapunov-based control scheme will be utilized in this research to design a relevant Lyapunov function, which operates as an energy function, for deriving the mobile manipulator's velocity-based controllers [24]. The Lyapunov function, also known as the total potentials, is the sum of all attractive and repulsive potential functions and will, therefore, be utilized to construct the attractive functions for the attraction to the target. In addition, the control laws will be devised such that the Lyapunov function is decreasing for all $t \geq 0$ and vanishes to zero as $t \to \infty$.

To guarantee that the end-effector converges to its target, it is essential for the mobile car-like platform to first converge to a pseudo-target which must prevail within the vicinity of the ultimate target (a, b). Let the centre of the pseudo-target be $\boldsymbol{x}_\tau = (\tau_1, \tau_2)$ and radius ς_T. The pseudo-target is described as the set:

$$T_1 = \{(z_1, z_2) \in \mathbb{R}^2 \colon (\mathrm{z}_1 - \tau_1)^2 + (\mathrm{z}_2 - \tau_2)^2 \leq \varsigma_\tau^2\}. \quad (4)$$

A target will be appended for the n-link prismatic robotic arm to navigate from its initial state after some time $t > 0$. The ultimate target for the end-effector is a disk with the center $\boldsymbol{x}_T = (a, b)$ and radius λ_T. It is described as the set:

$$T = \{(z_1, z_2) \in \mathbb{R}^2 \colon (\mathrm{z}_1 - \mathrm{a})^2 + (\mathrm{z}_2 - \mathrm{b})^2 \leq \lambda_T^2\}. \quad (5)$$

A. The two-step technique

The two-step algorithm initially proposed in [4] is utilized in this research to reinforce the LbCS in facilitating the motion planning and control of the mobile manipulator:

- **Step 1:** The car-like manipulator moves from its initial position, (x_1, y_1) to the pseudo-target, (τ_1, τ_2). At this moment, the end-effector is not attracted to its target till the centre of the manipulator is within a distance of $c > 0$ from the pseudo-target. This implies that $(\mathrm{x}_1 - \tau_1)^2 + (\mathrm{y}_1 - \tau_2)^2 > c^2$.
- **Step 2:** The end-effector will only be attracted to its target, (a, b), when the car-like manipulator navigates to a region within a distance of $c > 0$ from the pseudo-target.

B. System Equilibrium

The equilibrium point for the car-like manipulator system is defined as:

$$\mathbf{x}_e := (a, b, \theta_f, \phi_f, r_{1_f}, r_{2_f}, ..., r_{n_f}) \in \mathbb{R}^{n+3},$$

where r_n is the final extension of the last prismatic link.

IV. VELOCITY CONTROLLERS

A. Lyapunov Function Components

1) Pseudo-target Attraction: The attractive potential function describing the attraction of the car-like manipulator to its pseudo-target is given as:

$$H_1(\boldsymbol{x}) = \frac{1}{2} \left\| \boldsymbol{\kappa} - \boldsymbol{x}_\tau \right\|^2. \quad (6)$$

2) End-effector Target Attraction: The attractive potential function describing the attraction of the end-effector to its target is:

$$H(\boldsymbol{x}) = \frac{\varrho}{2} \left\| \boldsymbol{x} - \boldsymbol{x}_T \right\|^2. \quad (7)$$

To ensure that the motion of the mobile manipulator will be continuous at all time $t \geq 0$, and the end-effector does not get attracted to its target until the car-like platform's centre is within a distance of $c > 0$ from the pseudo-target, the following function is utilised:

$$\varrho = \begin{cases} 0, & \left\| \boldsymbol{\kappa} - \boldsymbol{x}_\tau \right\|^2 \geq c^2 \\ c^2 - \left\| \boldsymbol{\kappa} - \boldsymbol{x}_\tau \right\|^2, & \text{otherwise.} \end{cases} \quad (8)$$

3) Restrictions and Limitations of Prismatic Links: Since a prismatic joint facilitates a translational sliding movement between two links, the $(k+1)^{th}$ prismatic link cannot be fully inserted into the k^{th} link. Therefore, the restriction on the k^{th} prismatic link is that $r_k(t) \neq 0$ at any time t, that is $r_{k0} = r_k(0) > 0$ for $\{k, 1, 2, \ldots, n\}$. Moreover, the limitation is that $r_{kmax} - r_k(t) \geq r_0$ at any time t. In order to avoid these singularities, the following functions are considered:

$$S_k = r_k(t) \text{ and } Q_k = r_{kmax} - r_k(t),$$

where r_{kmax} is the total length of the k^{th} prismatic link.

B. A Lyapunov Function

Let $\gamma_k > 0$, and $\delta_k > 0$. Define for $k = \{1, 2, 3, ..., n\}$, a Lyapunov function of the form,

$$L(\mathbf{x}) = \eta H_1 + H(\boldsymbol{x}) \left(\sum_{k=1}^{n} \frac{\gamma_k}{Q_k} + \sum_{k=1}^{n} \frac{\delta_k}{S_k} \right). \quad (9)$$

Along a trajectory of system (3), there is

$$\dot{L}(\mathbf{x}) = \eta \dot{H}_1 + \dot{H}(\boldsymbol{x}) \left(\sum_{k=1}^{n} \frac{\gamma_k}{Q_k} + \sum_{k=1}^{n} \frac{\delta_k}{S_k} \right) - H(\boldsymbol{x}) \left(\sum_{k=1}^{n} \frac{\gamma_k}{Q_k^2} \dot{Q}_k + \sum_{k=1}^{n} \frac{\delta_k}{S_k^2} \dot{S}_k \right), \quad (10)$$

which can be simplified to

$$\dot{L}(\mathbf{x}) = p(\mathbf{x}) \dot{x}_1 + q(\mathbf{x}) \dot{y}_1 + f(\mathbf{x}) \omega + \sum_{k=1}^{n} g_k(\mathbf{x}) v_k, \quad (11)$$

where $p(\mathbf{x}) = \dfrac{\partial L(\mathbf{x})}{\partial x_1}, q(\mathbf{x}) = \dfrac{\partial L(\mathbf{x})}{\partial y_1}$, $f(\mathbf{x}) = \dfrac{\partial L(\mathbf{x})}{\partial \phi}$ and $g_k(\mathbf{x}) = \dfrac{\partial L(\mathbf{x})}{\partial r_k}$. Let there be a scalar $\psi, \rho, \alpha, \beta_k > 0$ for $k = \{1, 2, 3, ..., n\}$. Then, the velocity controllers of system (3) are

$$u_1(t) = -\psi p(\mathbf{x}(t)), u_2(t) = -\rho q(\mathbf{x}(t)),$$
$$\omega(t) = -\alpha f(\mathbf{x}(t)), v_k(t) = -\beta_k g_k(\mathbf{x}(t)). \quad (12)$$

C. Steering Control Laws

Let ξ be some arbitrary continuous positive function of x_1 and y_1. The steering control laws of the car-like manipulator is described as

$$\left.\begin{aligned} \nu &:= -\xi(p(\mathbf{x})\cos\theta + q(\mathbf{x})\sin\theta), \\ \varpi &:= \tfrac{2\xi}{L}(p(\mathbf{x})\sin\theta - q(\mathbf{x})\cos\theta). \end{aligned}\right\} \quad (13)$$

Hence, system (2) can be expressed as

$$\left.\begin{aligned} \dot{x}_1 &= -\xi p(\mathbf{x}), \\ \dot{y}_1 &= -\xi q(\mathbf{x}), \\ \dot{\theta} &= \tfrac{2\xi}{L}(p(\mathbf{x})\sin\theta - q(\mathbf{x})\cos\theta), \end{aligned}\right\} \quad (14)$$

which facilitates the position and orientation of the car-like mobile manipulator.

D. Maximum Velocities

The function $\xi = \xi(x_1, y_1) > 0$ guarantees that the car-like platform adheres to the velocities and steering angle restrictions of a vehicle. Given a positive real number m, from (13),

$$\left.\begin{aligned} |\nu| &\le \xi\left(m + |p(\mathbf{x})| + |q(\mathbf{x})|\right), \\ |\varpi| &\le \tfrac{2\xi}{L}\left(m + |p(\mathbf{x})| + |q(\mathbf{x})|\right). \end{aligned}\right\} \quad (15)$$

If the maximum translational speed is obtained as $\nu_{max} := max|\nu|$, then from the first inequality of (15),

$$\xi := \frac{\nu_{max}}{m + |p(\mathbf{x})| + |q(\mathbf{x})|}. \quad (16)$$

E. Maximum Steering Angle

Let ϑ be the steering angle. Then, the maximum steering angle is $\vartheta_{max} := max|\vartheta|$, where $0 < \vartheta_{max} < \frac{\pi}{2}$. Moreover, $|\nu_i| \le \nu_{max}$ and $\nu^2 \ge d^2\varpi^2$, where $d := \frac{L}{\tan\vartheta_{max}}$ are the constraints imposed on the translational and rotational velocity, ν and ϖ, respectively. If $|d| = \frac{L}{2}$, then $\tan\vartheta_{max} = 2$. Therefore, the maximum steering angle for the car-like manipulator is set at $\vartheta_{max} = tan^{-1}2$.

V. Stability Analysis

The Lyapunov function $L(\mathbf{x})$ is positive over the domain

$$D(L(\mathbf{x})) := \{\mathbf{x} \in \mathbb{R}^{n+3}, : S_k > 0, Q_k > 0, \\ \forall k = \{1, 2, 3, ..., n\}\}.$$

With respect to system (2), and with the control laws (13),

$$\begin{aligned} \dot{L}(\mathbf{x}) &= -\frac{1}{\xi}\left(\nu^2 + \frac{L^2}{4}\varpi^2\right) \\ &\quad -(\alpha(f(\mathbf{x}))^2 + \sum_{k=1}^{n}\beta_k(g_k(\mathbf{x}))^2) \le 0, \end{aligned}$$

$\forall \mathbf{x} \in D\big(L(\mathbf{x})\big)$. It is easy to see that $L(\mathbf{x}_e) = 0$, $L(\mathbf{x}) > 0 \ \forall \ \mathbf{x} \ne \mathbf{x}_e$ and $\dot{L}(\mathbf{x}) \le 0$.

VI. Simulation Results

Computer simulations were generated using Wolfram Mathematica 11.2 software. To achieve the desired results, a number of sequential Mathematica commands were executed. Before the algorithm is executed, the restrictions, limitations and values of the convergence parameters have to be stated using the brute-force technique. The positions of the pseudo-target and target, and initial state of the car-like manipulator have to be defined. The system was numerically simulated using the RK4 method (Runge-Kutta Method).

A. Example

In this example, a car-like manipulator with a revolute link and 3-link prismatic arm anchored at (10, 10) is considered. The dimensions of the car-like platform are $L = 8$ and $L_1 = 4$, while its safety parameters are $\epsilon_1 = \epsilon_2 = 0.5$. The coordinates of the pseudo-target and target are (40, 30) and (25, 40) respectively. The attraction region of the pseudo-target has a radius of $c = 1$. The length of the revolute link is $l = 6$, and initial extensions of the prismatic links are $r_{1_0} = r_{2_0} = r_{3_0} = 0.8$ with $r_{k_{max}} = 5.5$. Moreover, $\phi_0 = 0$ and $\theta_0 = 2.86515$. The convergence parameters are $\eta = 1$, $\gamma_k = \delta_k = 0.0001$ where $k = \{1, 2, 3\}$. The maximum translational velocity of the system is $\nu_{max} = 1$, and the maximum steering angle for the car-like vehicle is set at $\vartheta_{max} = tan^{-1}2$. As time evolves, the wheeled car-like manipulator moves from its initial position towards its pseudo-target without any attraction of the end-effector to its target. As shown in Fig 2, once the mobile platform is within a distance of $c = 1$ from its pseudo-target, the end-effector is subsequently attracted to its target. Fig 3 shows the evolution of the Lyapunov function and its time derivative along the trajectory of the system. The angular position of the robotic arm mounted on the car-like vehicle is measured counterclockwise from the longitudinal axis of the car-like manipulator as shown in Fig 4. It shows that $\phi(t) = 0$ until the car-like manipulator is at a distance $> c$.

VII. Conclusion

In this research, the LbCS approach is proposed to solve the motion control problem of a car-like mobile manipulator with an n-link prismatic arm in an obstacle free environment. The target convergence of both the car-like platform and the prismatic arm, restrictions and limitations of the prismatic links, and the steering controls of the system have been carefully incorporated into the control laws to ensure that a stable motion is achieved.

Due to technological advancements in mobile robotics, the commercialization of such automated car-like robots is expected to stimulate the market over the next years and boost demand for mobile robots in domestic applications such as vacuum cleaners and lawn mowers. The car-like mobile manipulator proposed in this research can have practical implications in tasks requiring dangerous work and moving in hazardous places, including applications such as agriculture, health care, underwater exploration, surveillance,

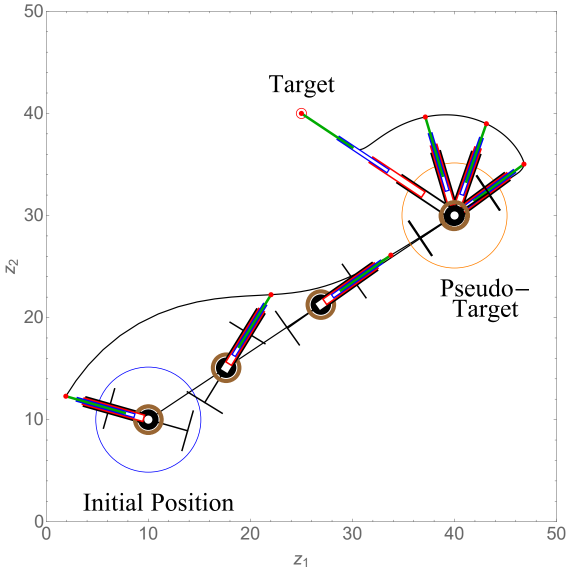

Fig. 2. Positions and orientations of the car-like manipulator at time $t = 0, 14, 29, 57, 109, 179$ and 499.

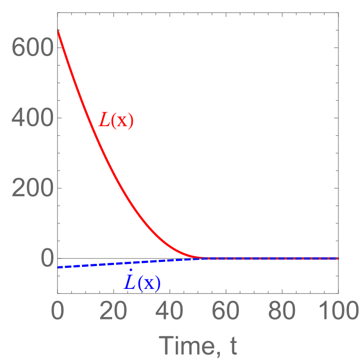

Fig. 3. Monotonically decreasing Lyapunov function and its time derivative.

military defense and security. As future work, switched velocity controllers will be considered for a car-like mobile manipulator with an n-link prismatic arm in an obstacle-ridden environment.

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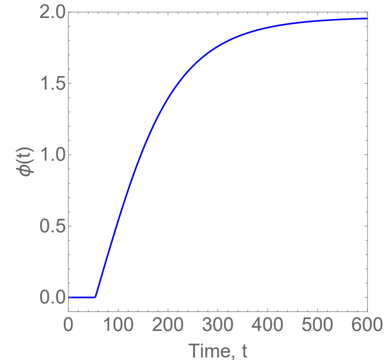

Fig. 4. Angular position of the robotic arm measured counterclockwise from the longitudinal axis of the car-like manipulator.

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