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Entertainment and Assistive Robot: Acceleration Controllers of an Autonomous Kids Personal Transporter (kPT)

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Abstract

Entertainment robots for children that keep them occupied are indirectly assistive robots for parents and caregivers while keeping busy with other work. This paper presents an autonomous kids' personal transporter (kPT) robot with an omnidirectional obstacle sensor of limited detection range, modeled in a two-dimensional space. A set of new nonlinear time-invariant stabilizing acceleration-based controllers designed using the Lyapunov-based control scheme (LbCS), a scheme for solving motion planning control problems using artificial potential fields. The derived controllers enable the kPT robot to navigate autonomously in a partially known environment by avoiding static obstacles to reach its target, where it achieves its equilibrium state. The results were validated through computer simulation using the Wolfram Mathematica software. This theoretical exposition could become the base work for a real prototype robot, which would be significant to working parents and caregivers, especially when they have to look after the kids while simultaneously carrying out their chores.

Keywords: Kids Personal transporter; Artificial potential fields; Obstacle avoidance; Acceleration controller; Lyapunov-based control scheme.

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1. Introduction

Human efforts to accomplish work in hostile and hazardous environments have resulted in various dangers to the people involved and blunders resulting in the loss of valuable capital and human lives. Robotic technology is constantly transforming human lifestyles to make them better and well-supported. Robots are now used in many fields, including navigation,[1] ocean cleanup and discovery,[2] retail supplementation,[3] health care needs,[4] human rescue, and agricultural assistance.[5] Robots are now also engineered with advanced design and functionalities beyond traditional boundaries, smoothly moving from essential caregiving tasks to diverse and captivating human leisure experiences through immersive entertainment for humans of various age groups. Recently, robots have been seen even in people's homes as social robots and other service or assistive robots. A social robot is an autonomous machine that uses a set of social behaviors and norms to interact with people and other social agents. In contrast, an assistive robot is a type of robot that can help a human with a variety of tasks, including learning, training, rehabilitation, and daily tasks. There are many robots available for a home environment, which could be categorized into humanoid robots,[6] animal robots,[7] and vehicle-like robots.[8] These robots focus on various age groups. For example, the iPal humanoid robot is designed to provide elderly companionship and care,[9] supplement personal care services, and provide protection through alarms for various medical emergencies, such as falling. On the other hand, BuddyBot is a virtual confidante that stands out as it caters specifically to depressed teens, offering them virtual therapy and messaging therapy sessions.[10] Thus, robots are becoming increasingly integrated into various aspects of society to provide support and assistance, particularly in the fields of healthcare and mental health.

In families with children, childcare duties may affect busy parents, making their lives more difficult at home and impacting their physical and psychological health. For instance, since the beginning of 2020, a new type of coronary pneumonia (COVID-19) has emerged, causing widespread concern worldwide.[11] The COVID-19 pandemic adversely affected mental health, with uncertain consequences for child-parent relationships.[12,13] According to research,[14] the

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COVID-19 pandemic has a negative impact on families' mental health and can result in sustained periods of elevated anxiety and depression symptoms. Further data reveals that children of very distressed caregivers, or caregivers who suffer from mental health consequences due to the COVID-19 pandemic, have the worst outcomes.[14] Furthermore, employees who telework for their employers often find that they cannot escape the constant demands of their jobs and may even experience a greater sense of work-related imbalance in their personal lives.[15,16] These show that children are victims of their caregivers' work-related stress, leading to being left out, and there is a need to find related solutions to help caregivers and children in these situations. In the past few decades, there have been considerable advancements in well-known robots for children, such as social, educational, assistive, or entertainment robots. For instance, the Petoi company, which manufactures futuristic bionic entertainment robots for kids intending to focus on robotic education with fun, introduced the Nybble robotic cat and the Bittle robotic dog in 2018 and 2020, respectively.[17] Their ability to accommodate a wide range of modules and sensors resulted in both Nybble and Bittle being utilized for entertainment and education, with children learning about robotics while entertained. Petoi robots are also compatible with the Petoi app, allowing easy control and programming. In addition, a modular robotic construction kit called ClicBot is designed for children's robotic education with fun. ClicBot consisted of various parts that could be configured for programming to walk, roll on motorized wheels, slither like a snake, grab things with a claw, and behave like a pet dog.[18] Targeted toward entertainment and education, ClicBot also brings children and adults together to share their programming to design functions for their ClicBot robot. Similarly, MarsCat promises to be the first bionic pet cat in the world.[19] These robots are available commercially, intended for children with higher cognitive skills, and they are required to program or teach their robots to build their cognitive skills in due process. Another essential form of children's entertainment is through kids' electric vehicles. The children either control these vehicles or their guardians remotely control them. These types of robot vehicles are mainly used for outdoor activities where there is a lower likelihood of accidents. For children, personal transportation options such as electric scooters (e-scooters, segways, hoverboards, and balancing scooters are available in the market. However, this personal transportation is age-restricted and may require a driving license in some countries. For instance, an e-scooter in California must be at least 16 years old and have a valid driver's license or permit. However, the age requirement for e-scooter rental companies in Los Angeles is stricter at 18 years old.[20] E-scooter injuries in the United States rose 222% from 4582 in 2014, when there were no scooter ride-share companies, to 14 651 in 2018, when scooter rentals took off across North America and Europe and recorded 33 injuries severe enough to require an ambulance service for hospitalization in 2019.[21] The most common reasons for accidents were speeding, losing control of the scooter, and colliding with a pothole or a stationary object, such as a pole. Kids with soft cognitive skills will find it extremely difficult to maneuver their electric vehicles, and this can cause accidents, leading to injuries.[22] Furthermore, toy robots are commercially produced for fun and recreation for children (ages four to eight years).[23] Similarly, Segway accidents resulting in fractures and concussions have been reported.[24] A lot of research is being carried out on assistive technologies, mainly assistive wheelchairs for children with disabilities, boosting their abilities to support themselves.[25,26] This research is motivated by the gap in the literature on the kids' personal transporter (kPT) robot. The existing research shows a noticeable lack of focus on autonomous assistive transport vehicles designed for entertainment and independent parenting assistance, especially compared to the significant attention only given to smart wheelchairs for disabled children. Thus, this research proposes a kPT robot that can serve the purpose of both assistive and entertainment transporter for children. This study aims to provide a theoretical exploration on the applicability of the Lyapunov-based control scheme (LbCS) in addressing the findpath problem of a kPT robot in partially unknown environment. In this research, a set of new nonlinear time-invariant stabilizing acceleration controllers of an autonomous kPT robot are constructed using the LbCS, which is a modification of the classical approach of artificial potential fields methodology. Utilizing LbCS attractive and repulsive potential functions will be created, which would be part of the total potential, to ensure target convergence, obstacle and collision avoidance and system adhering to its limitations and restrictions. The advantages of using LbCS are that it can implement control conditions, specifications, inequalities, and constraints of mechanical systems in the controllers through mathematical functions.[27] Moreover, the controllers are relatively easy to derive, are continuous, and inherit system asymptotically stable criteria as discussed in Refs. [1] and [28].

The main contributions of this paper are:

- The development of the kinematic equations of a proposed nonholonomic autonomous kPT robot with an omnidirectional obstacle sensor of limited detection range and two front diametrically opposed drive wheels. The omnidirectional sensor allows the kPT robot to navigate in a partially known environment, hence saving memory and computational time. However, Raj *et al.* (2020) provided a solution to motion planning and control of a robot where the robot requires global workspace information to complete tasks.[1]
- The new stabilizing nonlinear time-invariant continuous acceleration controllers of an autonomous kPT robot with zero turn radius maneuvering ability for navigation in a partially known environment containing static obstacles. Personal transporters such as Segways and e-scooters are controlled by their riders; hence, they must maneuver skillfully to avoid collisions and obstacles. However, there have been accidents where the riders control the personal transporter.[21] The

system proposed in this paper prioritizes rider safety. Moreover, in relation to the literature on autonomous kids' transportation, only assistive wheelchairs for children with mobility disabilities were focused on, whereas the proposed system is for all kids.[25,26] In Ref. [1], velocity-based controllers were used, whereas in this research, acceleration-based controllers are used to maintain a smooth velocity change to ensure rider comfortability.

The rest of the paper is organized as follows: A literature review on entertainment robots for kids is presented in Section 2. Section 3 describes LbCS, the method used to derive the acceleration controllers for the maneuvering kPT robot from its initial position to the target. Section 4 presents the kinematic model of a nonholonomic kPT robot. The derivation of the acceleration controllers of the robot is shown in Section 5. Section 6 discusses the stability analysis, and simulation results are discussed in Section 7. In section 8, a discussion of the research is provided. Finally, the paper is concluded in Section 9.

Children are typically charmed by robots and artificial intelligence, as the concept of machines that can think, learn, or perform tasks independently is highly appealing and sparks curiosity and excitement in many kids. Educational robots and interactive AI toys are designed for children to engage and entertain while teaching various skills, such as programming basics, problem-solving, or providing companionship. The interactive nature of these robots allows kids to explore technology in a fun and accessible way. Entertainment is an essential application of autonomous robotics, which has resulted in entertainment robots penetrating homes and schools.[29] Over the years, researchers have designed various types of autonomous robots for entertainment purposes for kids, which can be generally categorized as pet-type robots, humanoid, and wheeled robots.

Early research on automated technologies for children focussed on biologically inspired robots that served as pets and became sources of comfort and learning. According to Ref. [30], the world's first series of autonomous entertainment robots for children was introduced in 1999 by Sony's Digital Creatures Lab and Toshitada Doi in the form of robot dogs called artificial intelligence robot AIBO. These robot dogs were automated through the OPEN-R program and could interact with humans and their surroundings. The ERS-1000 version of AIBO was released in 2018 with artificial intelligence comprising various sensors, cameras,[31] and actuators with remarkable realism in expression and movement. Using 12 degrees of freedom, AIBO created a lifelike complex walking motion like a pet dog, making it popular amongst children.[30,31] After successfully implementing AIBO, researchers began investigating pet-type animal robots for kids' entertainment.[29] One such entertainment robot was a fast-moving, intelligent, and affectionate robot dog presented in 2016, known as the Wowwee Chip, which reacted efficiently to speech and touch commands.[32] However, the Wowwee Chip was non-programmable and only resembled the property of a pet dog. Another intelligent entertainment robot, MarsCat, was created by Elephant Robotics in 2019.[33] Despite its slow movement and limited flexibility, MarsCat was capable of controlling its own mobility, sensing touch, hearing sounds, recognizing faces, and interacting with toys, thus making it suitable for entertainment and education for children.[19]

Intelligent humanoid robots have effectively mixed kids' interests and curiosity with early childhood education for entertainment and learning purposes.[34] For example, the Buddy robot, developed by BlueFrog Robotics in 2014, was an adorable emotional humanoid that captivated social properties to engage with children in entertainment activities.[35] In 2015, Ioannou *et al.*[36] used NAO, a programmable humanoid robot developed by the French Aldebaran Robot Company, to show that humanoid robots could be used in preschools to boost kids' interest in learning while simultaneously keeping them entertained. Mousa *et al.* (2017) utilized the Conceptual Robotic Cube to attract preschoolers' attention to education, making them more engaged in learning activities.[37] Furthermore, the Moxie robot could help youngsters aged five to ten improve their social, emotional, and cognitive skills through game-based learning and lessons on turn-taking and eye contact.[38] However, as pointed out by Ziouzios *et al.* (2021),[35] humanoid robots for entertainment are generally more expensive when compared to other forms of entertainment robots.

In comparison to pet-type and humanoid entertainment robots, wheeled vehicle-like robots have the potential to be incorporated into the daily experiences of children and provide entertainment opportunities like mobility, ride-on, interactions, and participation with peers for play. Early researchers were reluctant to design autonomous vehicles for transporting children, mainly concentrating on assistive vehicular robots for kid's entertainment, as revealed by the Nicholson and Bonsalls 2002 survey of wheeled robots.[39] However, the initial work on robots for entertainment and companion purposes was described by Schraft *et al.* (2001) that were successfully used for purposes such as greeting visitors and tour guides and playing with a ball in a museum.[40] Each mobile robot was equipped with two differential drive two-wheeled drive systems, including four castor wheels for keeping the robots upright. At the same time, the safety laser sensors retrieved information using vehicle-to-infrastructure (V2I) communication to ensure collision avoidance with humans or obstacles. A collision-avoidance algorithm known as PolarBugwas designed by the authors for obstacle detection with a laser scanner and fast reaction and navigation in unstable environments.[41] The significant difference between PolarBug and other common obstacle avoidance algorithms was the direct processing of the laser scanner data, which enabled a very high efficiency of the algorithm.

Later, in 2009, Colak *et al.* introduced a commercial-type entertainment vehicle called the Line Following Robot with a passenger-carrying capacity that carried children through shopping malls and entertainment centers.[42] This entertainment robot worked with minimum human intervention and utilized highly sensitive infrared sensors and its control panel to increase safety and desired speed levels. A master microcontroller was used to process feedback signals from the sensors, which employed V2I and vehicle-to-vehicle (V2V) communication to facilitate motion and collision avoidance. However, the complexity of the workspace in which mobile robots operate continuously poses challenges for researchers. This complexity prompted Mercedes-Benz to test their robotic vehicle, Bertha, in 2013, using vision sensors with V2I communication to detect traffic lights and recognize their states.[43] The authors' findings revealed that the recognition rate needed improvements for traffic lights and objects at distances above 50 meters.

Assistive wheeled vehicle robots that provide mobility to children with mobility disabilities play a significant role in creating an inclusive society. Although independent mobility is crucial for children with severe movement disabilities, learning to use a motorized wheelchair could be challenging. In 2010, Crespo *et al.*[25] developed a prototype pediatric smart wheelchair for the entertainment of disabled kids by incorporating a webcam to achieve dynamic self-initiated movement in play areas of a structured environment. Later, in 2012, Soh and Demiris designed a smart pediatric wheelchair called Assistive Robotic Transport for Youngsters (ARTY),[26] enabling more disabled children to benefit from independent mobility. ARTY was colorful, easily transportable, had adjustable seats, and was relatively lightweight. A hybrid shared-control method consisting of the Combined Vector Field (CVF) and the Dynamic-Window Approach (DWA) algorithms was utilized for navigation. Despite the challenges provided by complex computer algorithms, the performance of the shared control methods was experimentally verified and worked successfully on children with physical and cognitive disabilities.[27] The kinematic and dynamic modeling of a human-wheelchair system is shown in Ref. [44], with the controller design based on two cascaded subsystems: an initialization controller, followed by a compensating controller that compensates for the dynamics of the human wheelchair system. Additionally, a fuzzy-logic-based method for pedestrian collision avoidance is proposed, and this algorithm is included in the preceding path-following control system. Recently designed a set of stabilizing velocity controllers for autonomous, multiple point-mass robots in the presence of wall-like rectangular planes in three-dimensional space while monitoring system restrictions and limitations using LbCS.[1] Similarly, in Ref. [27], the authors used LbCS to develop acceleration controllers for control laws to navigate multiple micro quadrotors with cylindrical obstacles in the workspace, suggesting that their method is simpler than the method proposed by Arantes *et al.*[45] and Esfandyari *et al.*[46] The singularities and limitations were treated as artificial obstacles in the LbCS algorithm, and the method's drawbacks were mentioned as algorithm singularities (local minima) could be introduced.

From this review, it is evident that apart from smart wheelchairs for disabled children, researchers have given very little attention to developing autonomous assistive transport vehicles that can carry a child around for entertainment purposes and provide independent parenting support. Such autonomous entertainment robots could become increasingly popular amongst kids due to attributes such as lack of supervision, reduced risk rates, and improved safety. The autonomous vehicle robot proposed in this research is a personal transporter for kids with two front driving wheels and one rear caster wheel (see Fig. 1). It uses the method of LbCS to navigate to its target by avoiding obstacles in its path. This technique of autonomous vehicle control could be easily adapted to create kids' transportation to assist parents in child care, provide support to children with special needs, and contribute to the kids' entertainment.

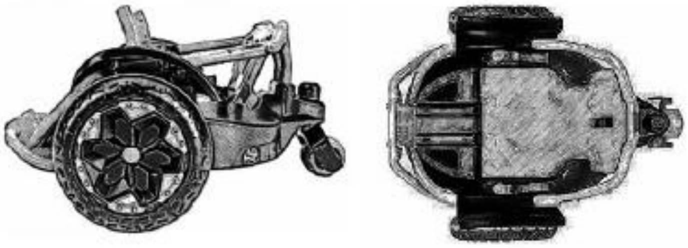


Fig. 1 Top and side elevation of a kPT with two front driving wheels with one rear castor wheel modified from Ref. [47].

2. Methodology and system modeling

2.1 Lyapunov-based control scheme

Lyapunov-based techniques, also known as the direct Lyapunov method, have the distinct advantage of allowing both design and analysis to be carried out inside a single framework. The Lyapunov direct method is based on the physical principle that a system with constant total energy dissipated must eventually reach an equilibrium point. LbCS is used in this study to create an artificial potential field. The primary goal of LbCS is to generate attractive and repulsive potential field functions. These functions are then combined into a total potential function from which time-invariant nonlinear velocity or acceleration controllers may be extracted. For target attraction and repulsion from various obstacles, LbCS includes constructing attractive and obstacle-avoidance functions whereby a positive tuning parameter is included in the numerator of each ratio, with the obstacle avoidance function in the denominator of each ratio. The successful use of LbCS to develop controllers could be found in Refs. [1] and [28].

Developing controllers using LbCS is simple, and the controllers are continuous, which is one of its strengths. When using LbCS, generating mathematical functions makes it simple to include control conditions, mechanical system restrictions, specifications, and inequalities of controllers. One limitation of Lyapunov-based analytical methodologies is that the settings used (while guaranteed to ensure closed-loop stability) may be overly cautious, degrading the system's quick responsiveness (possibility of algorithm singularities).[27] Figure 2 shows an example of the contour plot and 3D visualization of a Lyapunov function created over the workspace for a robot whose initial position is at (10,10). The dotted line depicts the robot's trajectory from its initial location to its target position (85, 100), which shows the robot avoiding the obstacle at (35, 45) with a radius of 10.

2.2 Nonholonomic kPT kinematic model

Definition: A front two-wheels driven kPT robot is a disk with radius r_s and is positioned at the centre of the mass of the robot, (x, y). The personal transporter is precisely described as the set

$$C = \{(z_1, z_2) \in \mathbb{R}^2 : (z_1 - x)^2 + (z_2 - y)^2 \leq r_s^2\}. \quad (1)$$

The kPT robot with an omnidirectional obstacle sensor that has a detection range of r_d is shown in Fig. 3. The robot has two diametrically opposed drive wheels of radius r and a rear free-wheeling castor for providing balance. The orientational angle of the kPT robot with respect to z_1-axis of the $z_1 z_2$ cartesian plane is θ. The distance from the centre of the two diametrically opposed wheels to the centre of the mass, (x, y), is λ. The angular velocities of the right and left wheels are $\dot{\phi}_R = v_R$ and $\dot{\phi}_L = v_L$, respectively. The distance between two wheels is 2δ. The personal transporter is enclosed by a circular protective region centred at (x, y), with radius $r_s := \sqrt{\xi^2 + (\eta + \lambda)}$ to ensure that the whole robot steers safely past obstacles. The configuration vector for the robot is,

$$\mathbf{x} = [x, y, \phi_R, \phi_L, v_R, v_L]. \quad (2)$$

Assuming no lateral slip motion on the front wheels and that there is pure rolling, with respect to (x, y), the following non-holonomic constraints of the robot need to be appropriately factored into the kinematic model:

$$\begin{aligned} \dot{y}\cos\theta - \dot{x}\sin\theta - \dot{\theta}\lambda &= 0, \\ \dot{x}\cos\theta + \dot{y}\sin\theta + \delta\dot{\theta} - r\dot{\phi}_R &= 0, \\ \dot{x}\cos\theta + \dot{y}\sin\theta - \delta\dot{\theta} - r\dot{\phi}_L &= 0. \end{aligned} \quad (3)$$

The kinematic model of the kPT robot with respect to its centre of mass $(x, y) \in \mathbb{R}^2$ is derived as:

$$\left.\begin{aligned} \dot{x} &= \frac{r}{2\delta}\big(v_R(\delta\cos\theta - \lambda\sin\theta) + v_L(\delta\cos\theta + \lambda\sin\theta)\big), \\ \dot{y} &= \frac{r}{2\delta}\big(v_R(\delta\sin\theta + \lambda\cos\theta) + v_L(\delta\sin\theta - \lambda\cos\theta)\big), \\ \dot{\theta}_0 &= \frac{r}{2\delta}(v_R - v_L), \\ \dot{\phi}_R &= v_R, \\ \dot{\phi}_L &= v_L, \\ \dot{v}_R &= a_R, \\ \dot{v}_L &= a_L. \end{aligned}\right\} \quad (4)$$

3. Results and discussion

3.1 Design of acceleration-based controllers

Consider a partially known workspace cluttered with $q \in \mathbb{N}$ stationary obstacles. The personal transporter has to maneuver to its target, avoiding the obstacles that get detected by the robot's omnidirectional sensor in its path.

Definition 1: The target for the kPT robot is a disk with centre (τ_1, τ_2) and radius r_s. It is described as the set

$$B := \{(z_1, z_2) \in \mathbb{R}^2 : (z_1 - \tau_1)^2 + (z_2 - \tau_2)^2 \leq r_s^2\}. \quad (5)$$

Definition 2: The k^{th} solid stationary obstacle is a disk with center (o_{k1}, o_{k2}) and radius $r_{O_k} > 0$. It is described as the set

$$O_k := \left\{(z_1, z_2) \in \mathbb{R}^2 : (z_1 - o_k)^2 + (z_2 - o_{k2})^2 \leq r_{o_k}^2\right\}$$

(6)

for $k \in \{1,2,3, \dots, q\}$.

Definition 3: Let r_d be the circular region of the robot with centre (x, y), s be the sensing zone of the robot and $r_d > r_s$. The Euclidean norm d_{O_k} is the closest point on the obstacle's boundary and the circle's boundary with radius r_s. Then

$$\beta_k = \begin{cases} \zeta\left(r_d^2 - d_{O_k}^2\right)^2, & \text{if } d_{O_k} \leq r_d \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

defines the robot's knowledge of any obstacles within its sensing zone as $r_s < s \leq r_d$, which enables it to navigate in a partially known environment.

3.1.1 Target Attraction

A radically unbounded target attraction function that will ensure that the kPT robot converges to its target is designed as follows:

$$V(\mathbf{x}) := \frac{1}{2}\left((x - \tau_1)^2 + (y - \tau_2)^2 + v_R^2 + v_L^2\right) \quad (8)$$

3.1.2 Stationary Obstacle Avoidance

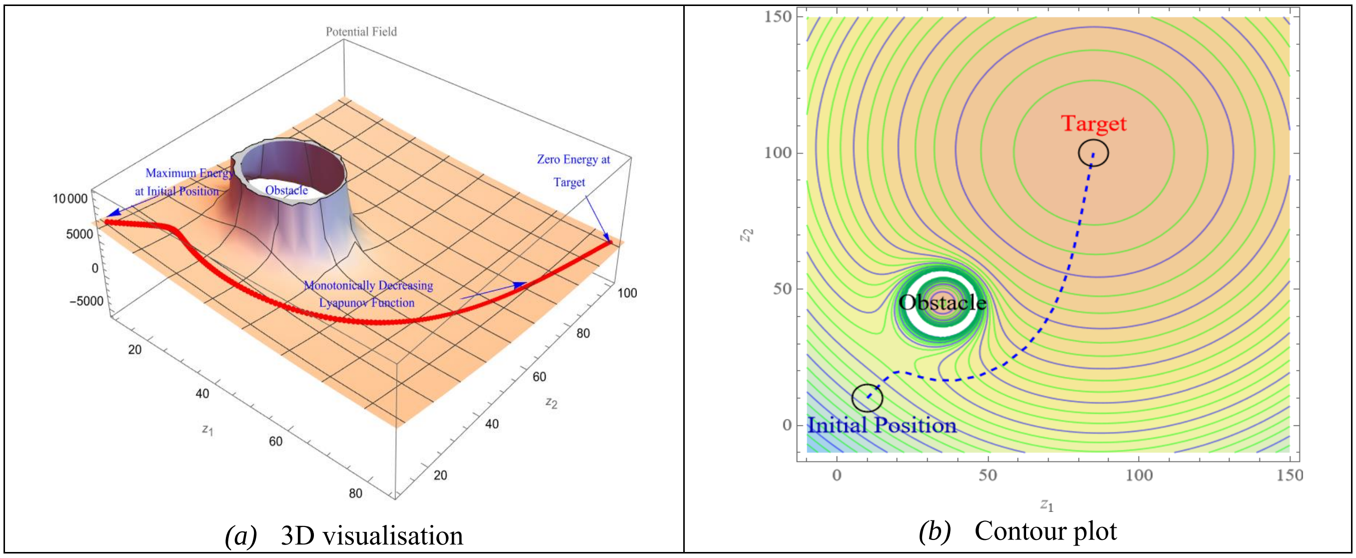
To avoid possible collisions with the k^{th} stationary solid obstacle, for $k \in \{1,2,3, \dots, q\}$, governed by equation (6), the following obstacle avoidance function will be utilized in the repulsive potential field functions:

$$E_k(\mathbf{x}) = \frac{1}{2}\left((x - o_{k1})^2 + (y - o_{k2})^2 - \left(r_s + r_{O_k}\right)^2\right) \quad (9)$$

3.1.3 Artificial Obstacles Avoidance

From a practical viewpoint, the angular velocities of the front right and left wheels have restrictions. Fig. 4 depicts an illustration of this restriction. The angular velocities of the right and left wheel are bounded as $|v_R(t)| < v_{\max}$ and $|v_L(t)| < v_{\max}$, where $v_{\max}$ is the maximum angular velocity of the front right and left wheels. The limitation on the velocities of the two front drive wheels of the kPT robot is included as artificial obstacles. The following avoidance functions are constructed for the restrictions on velocities that would be utilized in the repulsive potentials functions:

$$\begin{aligned} U_1(\mathbf{x}) &= \frac{1}{2}(v_{\max}^2 - v_R^2), \\ U_2(\mathbf{x}) &= \frac{1}{2}(v_{\max}^2 - v_L^2) \end{aligned} \quad (10)$$



(a) 3D visualisation *(b)* Contour plot

Fig. 2 An illustration of the Lyapunov-based control scheme.

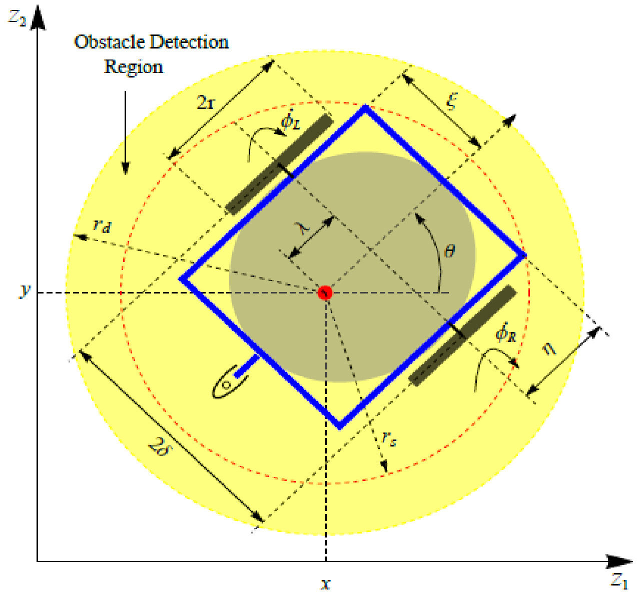


Fig. 3 kPT robot modelled as a wheeled mobile robot with two front driving wheels and one rear castor wheel.

3.1.4 Total potentials

Introducing positive control parameters α_1, α_2, and ζ, the total potentials for system (2) is as follows:

$$L(\mathbf{x}) = V(\mathbf{x}) + R(\mathbf{x})\left(\sum_{k=1}^{q}\frac{\beta_k}{E_k(\mathbf{x})} + \sum_{k=1}^{2}\frac{\alpha_k}{U_k(\mathbf{x})}\right) \qquad (11)$$

where

$$R(\mathbf{x}) := \frac{1}{2}\left((x-\tau_1)^2 + (y-\tau_2)^2\right) \qquad (12)$$

is an auxiliary function that will ensure that the nonlinear acceleration controllers vanish at the target.

3.1.5 Controller design

Along a trajectory of system (2),

$$\dot{L}(x) = \dot{V}(\boldsymbol{x}) + \dot{R}(\boldsymbol{x})\left(\sum_{k=1}^{q}\frac{\beta_k}{E_k} + \sum_{k=1}^{2}\frac{\alpha_k}{U_k}\right) - R(\boldsymbol{x})\left(\sum_{k=1}^{q}\frac{\beta_k \dot{E}_k}{E_k^2} + \sum_{k=1}^{2}\frac{\alpha_k \dot{U}_k}{U_k^2}\right), \qquad (13)$$

which can be rearranged, upon collecting terms with v_R, and v_L, as

$$\dot{L}(x) = f v_R + g v_L \qquad (14)$$

where the functions f and g, on suppressing $\mathbf{x}$, are defined as:

$$f = \frac{r}{2\delta}\left(\frac{\partial L}{\partial x}(\delta\cos\,\theta - \lambda\sin\,\theta) + \frac{\partial L}{\partial y}(\delta\sin\,\theta + \lambda\cos\,\theta)\right) + a_R\left(1 + \frac{\alpha_1 R}{U_1^2}\right), \qquad (15)$$

and

$$g = \frac{r}{2\delta}\left(\frac{\partial L}{\partial x}(\delta\cos\,\theta + \lambda\sin\,\theta) + \frac{\partial L}{\partial y}(\delta\sin\,\theta - \lambda\cos\,\theta)\right) + a_L\left(1 + \frac{\alpha_2 R}{U_2^2}\right). \qquad (16)$$

With the necessary substitutions carried out and introducing the convergence parameters $\sigma_1 > 0$ and $\sigma_2 > 0$ such that

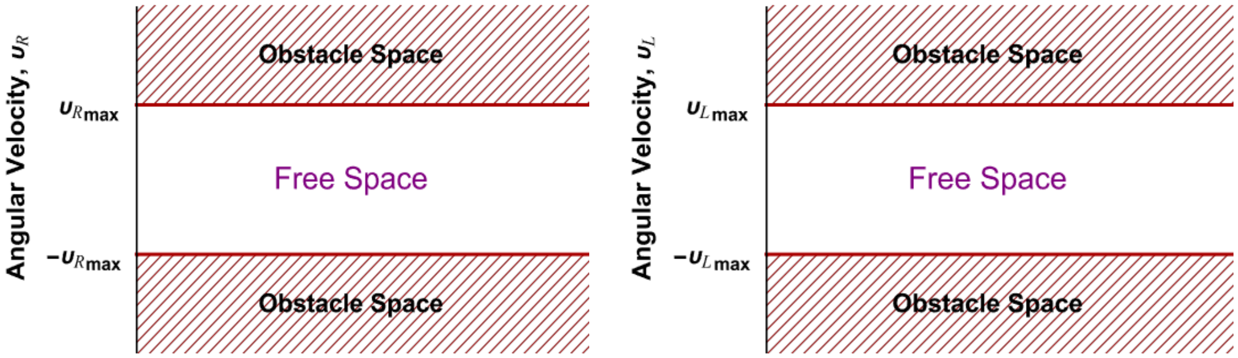
$$\dot{L} = -\sigma_1 v_R^2 - \sigma_2 v_L^2 \leq 0 \qquad (17)$$

then the controllers of system (2) are obtained as:

$$\left.\begin{aligned} a_R &= \frac{-U_1^2 r}{2\delta\left(U_1^2+\alpha_1 R(\mathbf{x})\right)}\begin{pmatrix} \frac{\partial L}{\partial x}(\delta\cos\theta - \lambda\sin\theta) + \\ \frac{\partial L}{\partial y}(\delta\sin\,\theta + \lambda\cos\,\theta) + \sigma_1 v_R + \frac{\partial L}{\partial \theta} \end{pmatrix}, \\ a_L &= \frac{-U_2^2 r}{2\delta\left(U_2^2+\alpha_2 R(\mathbf{x})\right)}\begin{pmatrix} \frac{\partial L}{\partial x}(\delta\cos\theta + \lambda\sin\theta) + \\ \frac{\partial L}{\partial y}(\delta\sin\,\theta - \lambda\cos\,\theta) + \sigma_2 v_L + \frac{\partial L}{\partial \theta} \end{pmatrix}. \end{aligned}\right\} \qquad (18)$$

3.2 Convergence analysis of the system

In this section, LaSalle's invariance principle is used to prove the convergence of the proposed Lyapunov-based control laws.[48] This principle is commonly used in control theory to study the stability properties of solutions of nonlinear systems of differential equations in $\mathbb{R}^n$ and evaluate convergence to established invariant sets. Suppose θ^* is the orientational angle of the kPT robot at the target, then the point $\mathbf{x}_e = (\tau_1, \tau_2, \theta^*, 0, 0, 0, 0)$ is an equilibrium point of system (2). Note that Lyapunov function defined in (5) is positive over the domain:



(a) Restriction on v_R *(b)* Restriction on v_L

Fig. 4 The obstacle space forms the artificial constraints that restrict the angular velocities v_R and v_L.

$$D(L(\mathbf{x})) := \{\mathbf{x} \in \mathbb{R}^6 : E_j(\mathbf{x}) > 0, U_k(\mathbf{x}) > 0, \forall j = \{1,2,3,\ldots,q\} \text{ and } \forall k = \{1,2,\}\} \tag{19}$$

Definition 4: A set $D(L(\mathbf{x}))$ is called an invariant set of the system (2) if any solution $\mathbf{x}(t)$ which starts from a point in $D(L(\mathbf{x}))$ at some time t_* also remains in $D(L(\mathbf{x}))$ at all times:[49]

$$\mathbf{x}(t_*) \in D(L(\mathbf{x})) \Rightarrow \mathbf{x}(t) \in D(L(\mathbf{x})), \forall t \in \mathbb{R} \tag{20}$$

This suggests that the set of all equilibrium points forms an invariant set. Furthermore, it should be noted that the domain of attraction of an equilibrium point is also considered an invariant set. As stated by LaSalle (1960), bounded solutions exhibit convergence towards the largest invariant subset of the set where the derivative of an appropriate energy function equals zero.[48]

Definition 5: Let ξ and J be numbers in R^+ and $\mathbf{x}(t)$ being a function of time. Let $\mathbf{x}_e$ be the set of all points $h \in D(L(\mathbf{x}))$ such that $\dot{L}(h) = 0$. Then, $\mathbf{x}(t)$ approaches a set $\mathbf{x}_e$ as t approaches infinity,[48] denoted by $\mathbf{x}(t) \to \mathbf{x}_e$ as $t \to \infty$, if

$$\forall \xi > 0, \exists J > 0, \forall t > J, \exists h \in \mathbf{x}_e, \|\mathbf{x}(t) - h\| < \xi. \tag{21}$$

As seen in Fig. 5(b), the Lyapunov function $L(\mathbf{x})$ diminishes progressively as:

$$\lim_{t\to+\infty} L(\mathbf{x}) = 0 \tag{22}$$

which is the lower bound of $L(\mathbf{x})$.

Theorem 1: Let's consider the existence of a scalar function $L(\mathbf{x})$ defined as in (11), which has continuous first-order partial derivatives in $D(L(\mathbf{x}))$ and is such that $L(\mathbf{x})(h) \leq 0$ in $D(L(\mathbf{x}))$. Let $\mathbf{x}_e$ be the set of points $h \in D(L(\mathbf{x}))$ such that $L(\mathbf{x})(h) = 0$. Let $N \in D(L(\mathbf{x}))$ and $\mathbf{x}_e$ be the largest invariant set in N. Then, ∃ a solution $\mathbf{x}$ starting in $D(L(\mathbf{x}))$ such that $\mathbf{x}(t) \to \mathbf{x}_e$ as $t \to \infty$.

Proof: Let $\mathbf{x}(t)$ be a function of time, and by continuity of the Lyapunov function provided in equation (11), $L(\mathbf{x}(t))$ is bounded. As $\dot{L}(\mathbf{x}) \leq 0, \forall \mathbf{x} \in D(L(\mathbf{x}))$, the function $L(\mathbf{x}(t))$ is non-increasing. Thus, the limit of $L(\mathbf{x}(t))$ should exist and is finite, and is denoted as Γ :

$$\lim_{t\to\infty} L(x(t)) = \Gamma. \tag{23}$$

Consider an arbitrary point denoted as w belonging to the set $\mathbf{x}_e$ in the ω-limit set. Here, $\mathbf{x}_e$ is a subset of N and represents a set of points that are approached by $L(w)$ as time approaches infinity. According to the definition of ω-limit sets, there exists a sequence d_t in $\mathbb{R}$.

$$\mathbf{x}(d_t) \to w, t \to \infty \tag{24}$$

By the continuity of $L(\mathbf{x}(t))$, it follows that

$$L(w) = \lim_{t\to\infty} L\big(\mathbf{x}(d_t)\big) = \lim_{t\to\infty} L(\mathbf{x}(t)) = \Gamma \tag{25}$$

This indicates that for all w in the ω-limit set $\mathbf{x}_e$, the function $L(\mathbf{x}(t))$ has the same value:

$$L(\mathbf{x}(t)) = \Gamma, \forall w \in \mathbf{x}_e \tag{26}$$

By the invariance of $\mathbf{x}_e$, if $w \in \mathbf{x}_e$, then $\mathbf{x}(t) \in \mathbf{x}_e \forall t \in \mathbb{R}$ which suggests that $L(\mathbf{x}(t)) = \Gamma \forall t \in \mathbb{R}$, that is, a constant function of time, t, and should have a derivative of zero, as demonstrated by Theorem (1). Therefore, $\mathbf{x}_e$ is an invariant set, and $\mathbf{x}(t)$ converges to $\mathbf{x}_e$ as $t \to \infty$.

The equilibrium point $\mathbf{x}_e$ is stable and all individual solutions of (6) converge to their final configurations $\mathbf{x}_e$, where $L(\mathbf{x}_e) \equiv 0$, given $\mathbf{x}_e \in D(L(\mathbf{x}))$, as $\dot{L}(\mathbf{x})$ is negative definite. The equilibrium point $\mathbf{x}_e$ of system (2) is stable, with $L(\mathbf{x}_e) \equiv 0$. Theorem (1) demonstrates that the bounded solutions of system (2) converge to the invariant set $\mathbf{x}_e$, a subset of N.

3.3 Simulation results

The results were validated using simulations generated using Wolfram Mathematica 12.3 software. Several sequential Mathematica commands were executed to achieve the desired simulation results. System (2) was numerically simulated using the RK4 method (Runge-Kutta Method. The control parameters were assigned values through brute-force.

Example 1 Consider a kPT robot to move from its initial configuration to a designated final configuration, avoiding an obstacle in its path. For this example, Table 1 shows the numerical values of the constraints and control and convergence parameters used for the kPT robot. The kPT robot has to maneuver to its target, avoiding the static obstacle in its way. As time evolves, the robot moves to its target, as shown in Fig. 5(a). The forward, backward, turning, and zero-turn radius maneuvering are present in this example. Fig. 5(b) shows the evolution of the monotonically decreasing $L(\mathbf{x})$ and its time derivative. This indicates that the kPT robot is converging to its target. The angular velocities, v_R, and v_L of the kPT robot are shown in Fig. 5 (c). The negative velocities of the wheels indicate that the kPT robot is in reverse mode, and deceleration demonstrates that it is approaching its target.

Table 1. Numerical values of the initial states, constraints, and control and convergence parameters of the kPT robot.

Initial Configuration	
Rectangular position	$(x_0, y_0) = (10{,}10)$
Initial orientation	-1.69
Constraints	
Dimensions	$\delta = 5, r = 2, \lambda = 2, \eta = 4, \xi = 3.5$
Target location	$(\tau_1, \tau_2) = (100{,}100)$
Omnidirectional Detection range	$r_d = 10$
Stationary obstacle Position	$(o_{11}, o_{12}) = (50{,}50)$
Radius of fixed obstacle	$r_{o_1} = 10$
Maximum angular velocities	$v_{R\max} = v_{L\max} = 1$
Control parameters	
Artificial obstacle avoidance	$\alpha_1 = \alpha_2 = 0.001$
Obstacle avoidance amplification	$\zeta = 0.0001$
Convergence	$\sigma_1 = \sigma_2 = 500$

Example 2 Consider the kPT robot to move from its initial configuration to a designated final configuration, avoiding three randomly positioned obstacles in its workspace. Here, Table 2 only provides the numerical values of the initial states, constraints, and control and convergence parameters used for the kPT robot for this example, which is different from Example 1. The kPT robot has to maneuver to its target, avoiding the static obstacle in its way. As time evolves, the kPT robot moves to its target, avoiding the obstacles as shown in Fig. 6(a). The evolution of $L(\mathbf{x})$ and its time derivative is similar to Fig. 5(b) of Example 1. The angular velocities, v_R, and v_L of the kPT robot are shown in Fig. 6(b).

Example 3 The kPT robot moves from its start to a predetermined final configuration while avoiding five randomly placed obstacles in its workspace. This example again uses the numerical values of the initial states, restrictions, control, and convergence parameters utilized for the kPT robot as provided in Table 2. As time evolves, the kPT robot moves to its target, avoiding the randomly placed obstacles as demonstrated in Fig 7(a). The evolution of $L(\mathbf{x})$ and its time derivative is similar to Fig. 5(b) of Example 1. The angular velocities, v_R and v_L of the kPT robot are shown in Fig. 7(b). The trends seen are similar to those from Example 1 and 2.

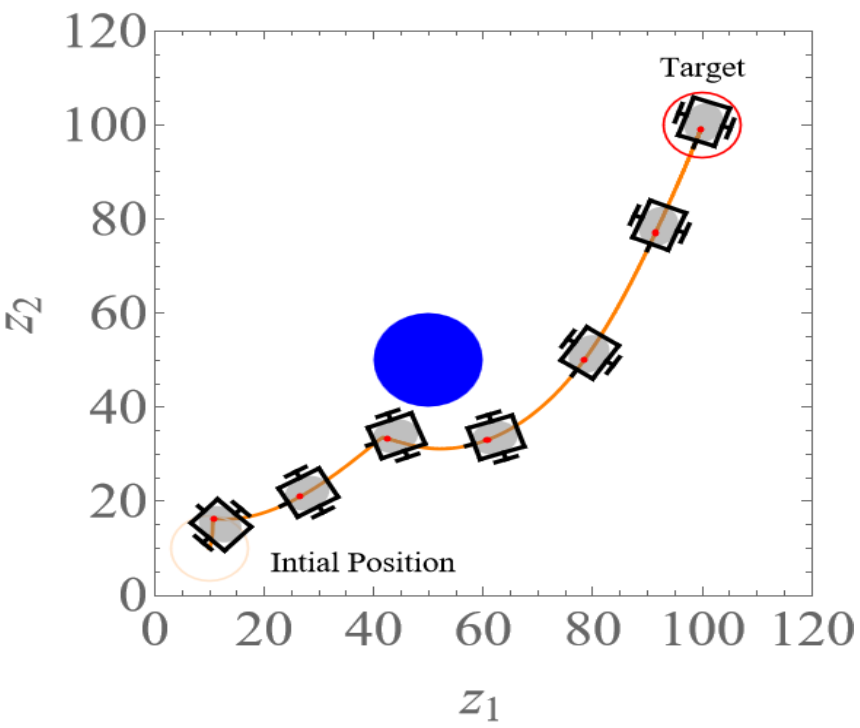
3.4 Discussion

There has been significant development in social robots for kids, but there is a lack of research on kPT robots. As mentioned in Ref. [21], accidents involving e-scooters are mainly due to riders' faults. The e-scooters do not have any sensing technique to avoid obstacles, and the rider takes complete control of the e-scooters. A safer kPT robot is essential as it could be an assistive system for parents and caregivers and an entertainment robot for kids. This paper presents stabilizing nonlinear time-invariant continuous acceleration controllers for an autonomous kPT robot, enabling it to safely navigate in an obstacle-cluttered environment whereby its rider does not need to steer the transporter for obstacle avoidance. The kPT robot is equipped with an omnidirectional sensor of limited detection range, which will ensure obstacle avoidance and safe navigation in cluttered environments. The robot also has two diametrically opposed frontdrive wheels and a rear free-wheeling castor, which enables it to navigate in a partially known environment. The kPT robot does not need information about the entire workspace, resulting in memory and computational time savings. For a comfortable ride for kids in an obstacle-ridden environment, the kPT robot's stabilizing acceleration controllers of the front wheels are designed using LbCS. Designing controllers using LbCS offers the simplicity of sidestepping complex, multi-system scenarios and can reduce the high mathematical and computational costs associated with more advanced control systems.[45,46] The LbCS method used in this paper is a classical method of motion planning and control that provides continuous controllers whereby system singularities and limitations could always be included as artificial obstacles. The effectiveness of the acceleration controllers and system's robustness is evident from the numerical examples shown in Figs. 5, 6 and 7.

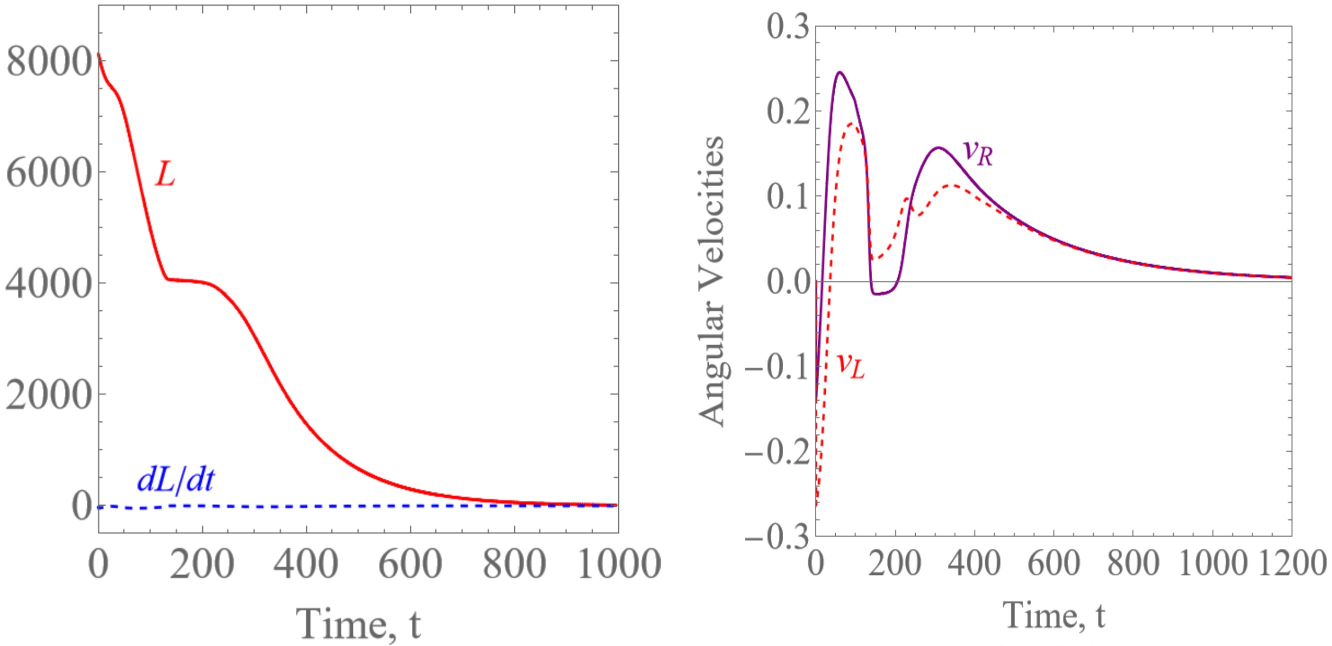
The kPT robot is fully automated; that is, the rider is not required to control it, and since it is an acceleration-controlled system, it would provide a comfortable ride for children with lower cognitive skills and disabilities. The kPT robot

Table 2. Numerical values of the initial states, constraints, and control and convergence parameters of the kPT robot.

Initial Configuration	
Rectangular position	$(x_0, y_0) = (110{,}10)$
Constraints	
Target location	$(\tau_1, \tau_2) = (10{,}100)$
Stationary obstacle Positions	Randomized
Radius of fixed obstacles	Randomized between 2 and 10



(a) Position and orientation at different times.



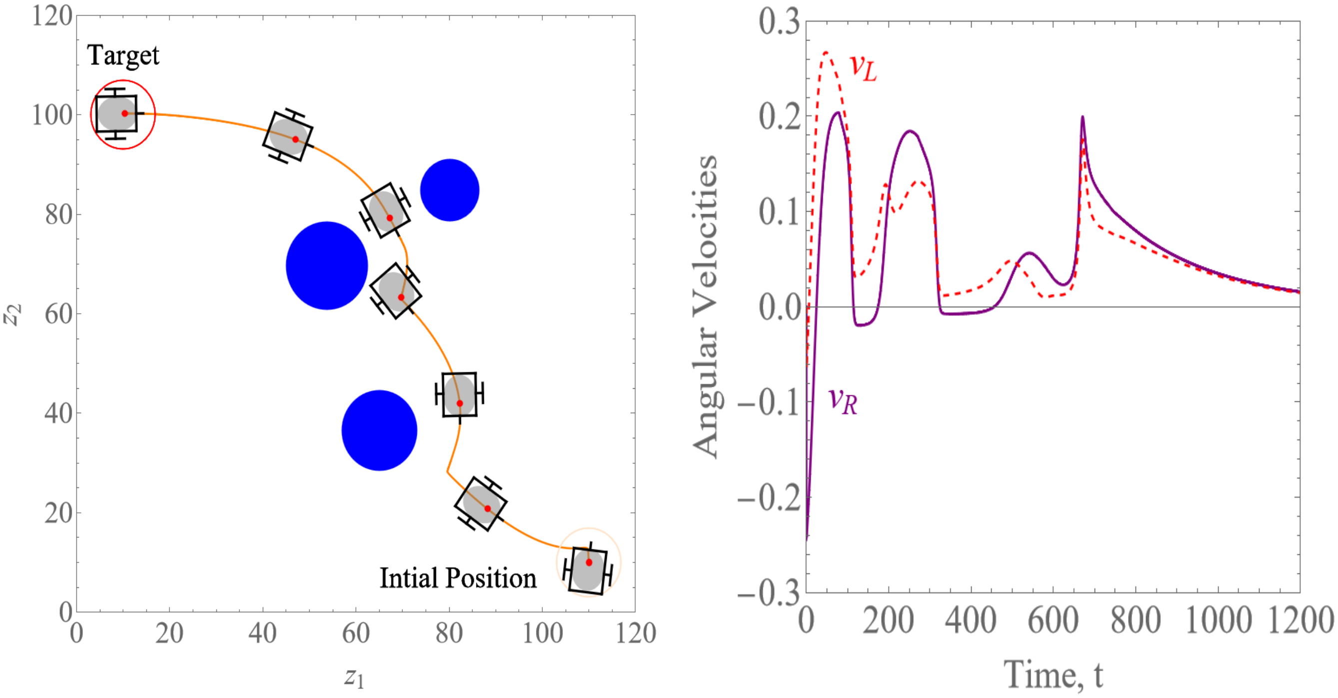
(b) Lyapunov function and its derivative.

(c) Angular velocities.

Fig. 5 (a) Position and orientation of the kPT robot at $t = 27, 79, 179, 299, 399, 599$ and 1400. The trajectory of the robot is shown in orange. (b) Monotonically decreasing Lyapunov function and its time derivative. (c) The front right and left wheels' angular velocities of the kPT robot show rapid deceleration as it approaches the target.

navigates through the partially known environment unlike in research papers,[1,29] autonomous robots need global environmental information to complete their tasks. The robot presented in Ref. [1] has velocity controllers; hence, it will contain sharp changes in velocities, which will not be a wise technique if used on the kPT robot; thus, the kPT robot presented in this paper is acceleration-controlled, which ensures smooth change in velocities ensuring rider comfort as shown in Figs. 5(c), 6(b) and 7(b).

This research has provided a solution to develop kids' personal entertainment robots for all age groups. All groups of children can use the transporter in this research as the controls are automatic. This can provide child caregivers with some assistance where children can be left in this personal transportation with a comfortable ride within the constrained home environment while they are doing their work.



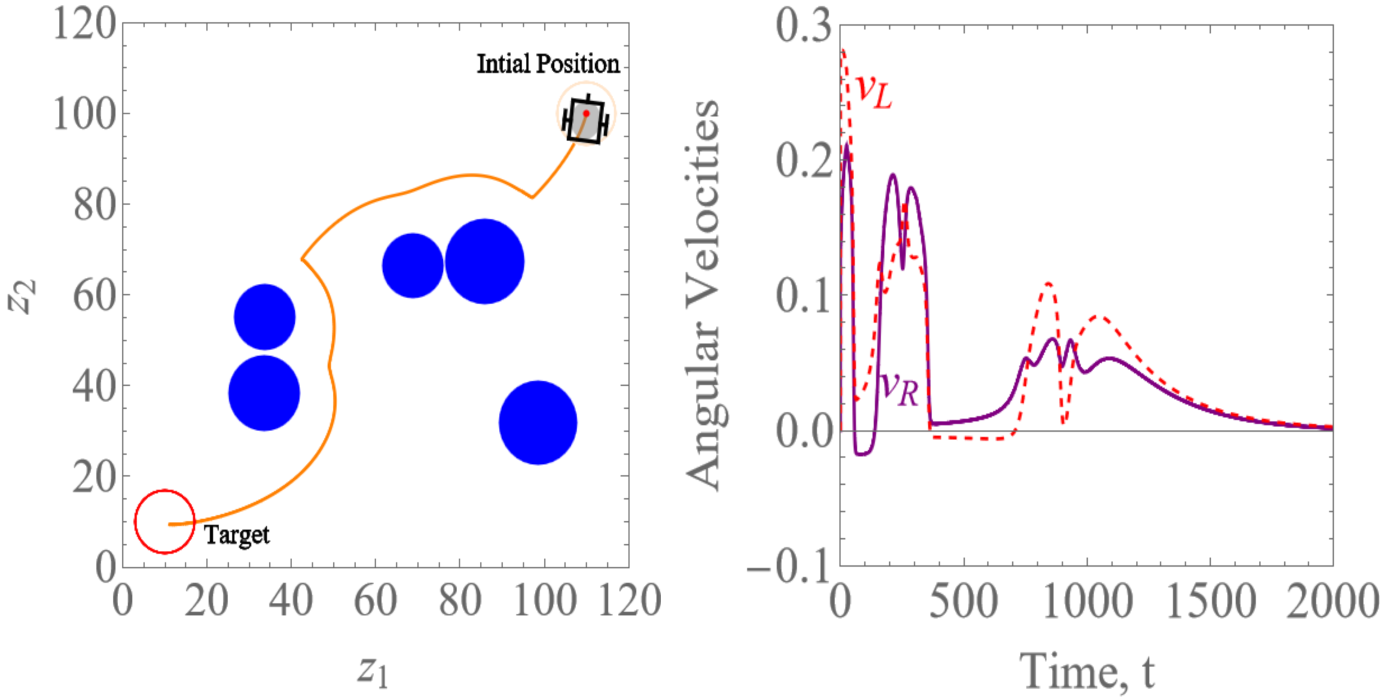
(a) Position and orientation at different times.

(b) Angular velocities

Fig. 6 (a) Position and orientation of the kPT robot at $t = 0, 79, 229, 344, 669, 799$ and 2000. The trajectory of the robot is shown in orange. (b) The front right and left wheels' angular velocities of the kPT robot show rapid deceleration as it approaches the target.

3.5 Limitation

Even though the paper provides practical application for kPT, there are important considerations when implementing the proposed system. These include stability in different environments, recognizing the limited weight capacity, analysing the risks for children while using the transporter and ensuring accurate real-time mapping and localization. The study was conducted at a fundamental level, and it is important to acknowledge its limitations, which are open to further research. This research paper presents a theoretical exposition only of the LbCS method in addressing motion planning and control of personal transporters for children. The controllers



(a) Position and orientation at different times.

(b) Angular velocities

Fig. 7 (a) Position and orientation of the kPT robot at $t = 0, 79, 229, 599, 849, 1099$ and 2000. The trajectory of the robot is shown in orange. (b) The front right and left wheels' angular velocities of the kPT robot show rapid deceleration as it approaches the target.

were only verified through mathematical proofs and software simulations to demonstrate the effectiveness of acceleration-based control principles, and the authors limited themselves to numerical proofs and computer-based simulations of interesting scenarios. However, no physical robot was used to verify the technique experimentally. One of the drawbacks of LbCS is the presence of algorithm singularities in the form of local minima. The problem of local minima was solved through brute force by using specific initial conditions, control, convergence, and avoidance parameters. This research only considers static obstacles and not a dynamic environment. However, various obstacles with different shapes and sizes may also be dynamic in real-life situations. Furthermore, no comparative studies exist between the proposed method and other motion planning and control techniques to determine the LbCS method's advantages and performance over other motion planning and control techniques. Thus, comparative studies between other methods are still an open research problem for future studies.

4. Conclusion

The gap in the literature shows that there is a need for autonomous assistive transport vehicles to carry a child around for entertainment and provide independent parenting support. This paper presented the design of a new kPT robot equipped with an omnidirectional obstacle sensor of limited detection range, two diametrically opposed front drive wheel, and a rear free-wheeling castor. Since the robot is intended for kids, rider comfortability was given higher priority, and acceleration controllers were given priority over velocity controllers. Using the LbCS, the nonlinear time-invariant stabilizing continuous acceleration controllers of the front right and left wheels of the robot were designed, which enabled the robot, governed by its kinematic equations, to navigate from an initial position to a target location in the presence of static obstacles. During the navigation process, the kPT robot uses its omnidirectional obstacle sensor to communicate with the static obstacles in the sensing zone, and it does not require global workspace information to reach its target. The interaction of the three central pillars of LbCS - smoothness, safety, and shortest path - contributes to the acceleration controllers' cost-effectiveness, efficiency and time effectiveness. This innovative approach is a significant advancement in motion control and provides advantages over heuristic approaches, which can be unpredictable and unstable motion in constrained environments. Artificial intelligence motion planning and control methods may not be suitable for every situation as they are complex and expensive. There are possibilities for introducing algorithm singularities, which is a drawback of LbCS. The controllers are continuous, but it is impossible to achieve in actual applications and asymptotic stability can only be demonstrated. This research is a theoretical exposition where LbCS applicability was investigated, and we limited ourselves to displaying the acceleration controllers' effectiveness through numerical proofs and computer-based solutions. The proposed kPT robot in this paper can be used by the industries for the prospects of production and implementation of a prototype robot.

A comparative study between LbCS and other heuristic approaches of motion planning and control will be conducted in future research, including dynamic environments. A hybrid system could be formed, combining the controllers presented in this research with the consideration of heuristic approaches to inherit the benefits of LbCS and the benefits of the heuristic methods and exclude the disadvantages of combined methods. In a statistical comparative study, a better motion planning and control method will be developed to provide autonomous control, which could be used on experimental prototype robots for more complex environments. The kPT transporter has the potential to become a popular form of entertainment for children living in smart cities. With modern technology and inventive design, this form of transportation may provide a new, and thrilling experience for children.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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