Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 55(1), 32–40(2014)

Mohsen Moradi Dalvand, Bijan Shirinzadeh, Saeid Nahavandi

Swing-Up and Stability Control of Wheeled Acrobot (WAcrobot)

DOI 10.7305/automatika.2014.01.109
UDK 681.511.4.07-53:004.896
IFAC 2.3.2; 1.2

Original scientific paper

In this paper the Wheeled Acrobot (WAcrobot), a novel mechanical system consisting of an underactuated double inverted pendulum robot (Acrobot) equipped with actuated wheels, is described. This underactuated and highly nonlinear system has potential applications in mobile manipulators and leg-wheeled robots. It is also a test-bed for researchers studying advanced methodologies in nonlinear control. The control system for swing-up of the WAcrobot based on collocated or non-collocated feedback linearisation to linearise the active or passive Degree Of Freedom (DOF) followed by Linear Quadratic Regulator (LQR) to stabilise the robot is discussed. The effectiveness of the proposed scheme is validated with numerical simulation. The numerical results are visualised by graphical simulation to demonstrate the correlation between the numerical results and the WAcrobot physical response.

Key words: Double Inverted Pendulum, Wheeled Robot, Underactuated Robot, Partial Feedback Linearisation, Linear Quadratic Regulator (LQR), Stabilisation

Njihanje i upravljanje stabilnošću koturajućeg Acrobota. U članku je opisan koturajući Acrobot (WAcrobot), novi mehanički sustav koji se sastoji od podupravljanog robota u obliku dvostrukog inverznog njihala (Acrobot) opremljenog s aktuiranim kotačem. Ovaj podupravljani i izrazito nelinearni sustav ima potencijalnu primjenu u mobilnim manipulatorima i robotima na kotačima. Također služi kao testni model za istraživače koji proučavaju napredne metode nelinearnog upravljanja. U radu je opisan sustav upravljanja za podizanje WAcrobot-a u ispravan položaj baziran na metodama kolocirane i nekolocirane eksterne linearizacije za linearizaciju aktivnog ili pasivnog stupnja slobode, i linearnom kvadratičnom regulatoru za stabilizaciju robota. Učinkovitost predviđene metode je validirana simulacijskim rezultatima. Rezultati su prikazani u obliku animacije kako bi se demonstrirala korelacija između simulacijskih odziva i fizičkog odziva WAcrobota-a.

Ključne riječi: dvostruko inverzno njihalo; robot na kotačima; podupravljani robot; parcijalna eksterna linearizacija; linearni kvadratični regulator; stabilizacija

1 INTRODUCTION

The inverted pendulum system is a perfect test-bed for the design of a wide range of classical and contemporary control techniques. Its applications range widely from robotics to space rocket guidance systems, but originally, these systems were used to illustrate ideas in control theory. Due to their inherent nonlinear nature, they have remained useful and they are now used to illustrate various ideas emerging in the field of modern nonlinear control.

There are different types of the inverted pendulum systems offering a variety of interesting control challenges. The common types are the single inverted pendulum on a cart [1,2], the double inverted pendulum on a cart [3,4], the double inverted pendulum with an actuator at the first joint only (Pendubot) [5], the double inverted pendulum with an actuator at the second joint only (Acrobot) [6, 7], the rotational single-arm pendulum [8–11], and the rotational two-arm pendulum [12]. The control techniques involved in inverted pendulum systems are also numerous, ranging from simple conventional controllers to advanced control techniques based on modern nonlinear control theory. A vast range of contributions exists for the stabilisation of different types of inverted pendulums [1, 8, 13, 14]. Besides the stabilisation aspect, the swing-up of single and double inverted pendulum systems is also addressed in the literature, e.g. swing-up of classic single pendulum on a cart [8, 15], Acrobot and Pendubot [5, 6] and the rotary pendulum [11, 16]. Beyond non-mobile inverted pendulum systems, wheeled inverted pendulum mobile robots or commonly known as balancing robots e.g., Segway [17], Quasimoro [18], and Joe [19], have also induced much interest and extensive controller developments have been achieved by researchers over the last decade [20–23].

In this paper, the swing-up control problem of the WAcrobot from its natural equilibrium point called pendant position to any arbitrarily small neighbourhood of the upright equilibrium point called inverted position and then switching to balance control problem, is investigated. The design of the swing-up controller is based on the notion of partial feedback linearisation of underactuated systems [24] that linearises the active or passive DOF(s) of the WAcrobot. The Linear Quadratic Regulator (LQR) controller is employed to stabilise the WAcrobot around the inverted equilibrium position. The effectiveness of the proposed control system is verified using numerical simulation visualised by graphical simulation to illustrate the physical response of the WAcrobot.

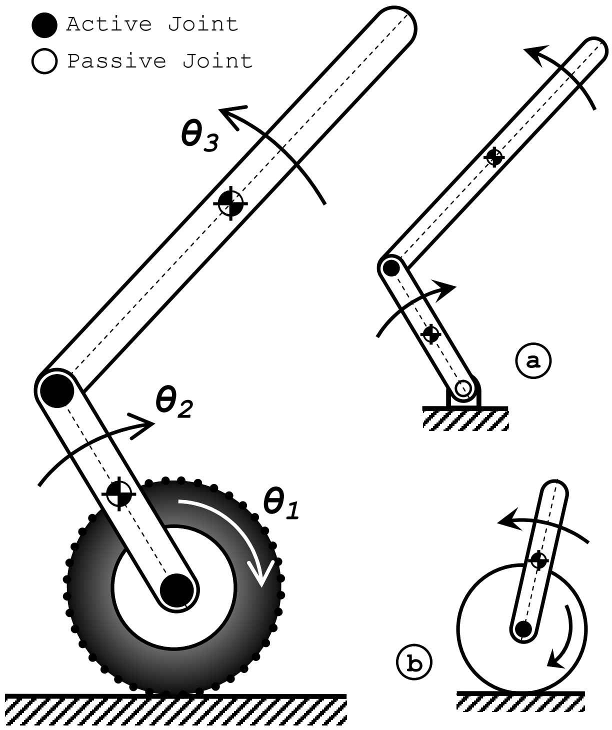

Fig. 1. WAcrobot, Acrobot (a) and Wheeled Inverted Pendulum (b)

The rest of the paper is organised into five sections. In the next section, the WAcrobot mechanism is explained and its model is schematically described. In section 3, the stabilisation controller and the swing-up controller are discussed and the mode switching approach is discussed. Numerical and graphical simulations results are demonstrated in section 4. Section 5 gives conclusion.

2 THE WACROBOT

The WAcrobot (Figure 1) is an underactuated system consisting of an Acrobot, a double inverted pendulum with actuator at the second joint only (Figure 1-a), that is equipped with actuated wheels and is able to move [25]. In other words, the WAcrobot is the combination of an Acrobot and a wheeled inverted pendulum robot (Figure 1-b). The mathematical model of the WAcrobot can be derived in the form of the Euler-Lagrange equations as:

Table 1. Definition of Parameters

Parameter	Definition
$\theta_i(i=1,2,3)$	Angular rotation of wheels and pendulums
$m_i(i=1,2,3)$	Mass of wheels and pendulums
$l_{ci}(i=2,3)$	Length from the joint to the centre of the gravity of pendulums
$l_i(i=1,2,3)$	Radius of wheels and length of pendulums
$I_i(i=1,2,3)$	Inertia moment around the centre of gravity

$$M_{11}\ddot{\theta}_1 + M_{12}\ddot{\theta}_2 + M_{13}\ddot{\theta}_3 + H_1 + G_1 = \tau_1 \quad (1)$$
$$M_{21}\ddot{\theta}_1 + M_{22}\ddot{\theta}_2 + M_{23}\ddot{\theta}_3 + H_2 + G_2 = 0 \quad (2)$$
$$M_{31}\ddot{\theta}_1 + M_{32}\ddot{\theta}_2 + M_{33}\ddot{\theta}_3 + H_3 + G_3 = \tau_2 \quad (3)$$

where θ_1, θ_2 and θ_3 are angular positions of wheels, first and second pendulum respectively, $M(\theta)\epsilon\mathbb{R}^{3\times3}$ is the symmetric, positive definite inertia matrix, $H\epsilon\mathbb{R}^3$ contains Coriolis and centrifugal terms, $G(\theta)\epsilon\mathbb{R}^3$ contains gravitational terms and $\tau = [\tau_1\ 0\ \tau_2]^T$ is the input generalised force vector produced by two actuators at wheels and the second pendulum. This equation represents the underactuated system of the WAcrobot including two inputs (τ_1 and τ_2), two active DOFs (θ_1 and θ_3) and one passive DOF (θ_2). Parameters of the WAcrobot are defined in Table 1.

3 SWING-UP CONTROLLER

The swing-up controller of WAcrobot is achieved by rolling the wheels within the limited travel while forcing the actuated or not actuated pendulums to track the proposed trajectories in order to guarantee that eventually trajectories enter the basin of attraction of the balance controller, which is in turn designed to exponentially stabilise the inverted equilibrium state. The swing-up controller of the WAcrobot is designed based on collocated or non-collocated partial feedback linearisation techniques [26] followed by switching to the balancing controller based on Linear Quadratic Regulator (LQR).

3.1 Collocated Linearisation

Collocated linearisation refers to a control technique that linearises the equations associated with the active DOFs ($y = [\theta_1\ \theta_3]^T$).

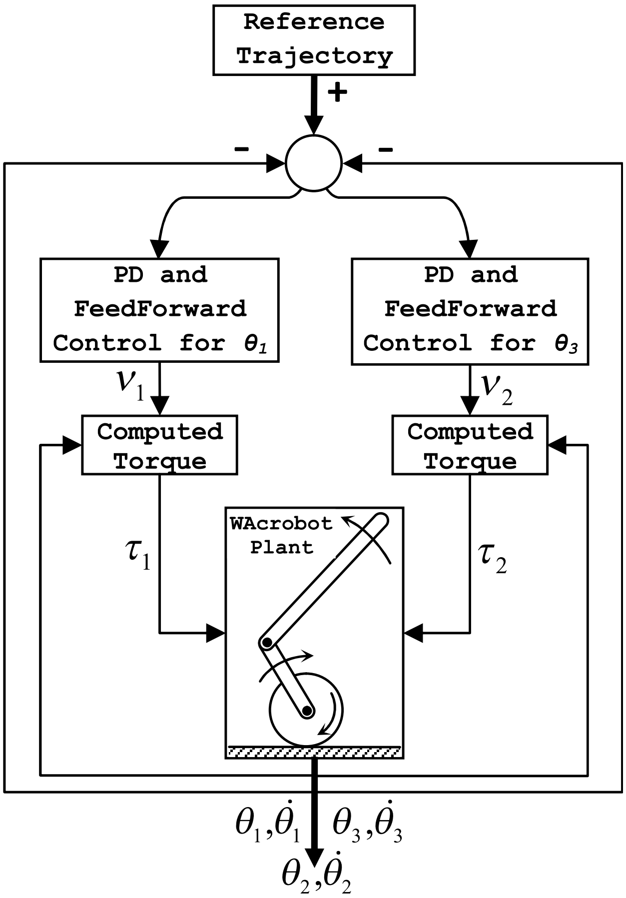

Fig. 2. Block diagram of the collocated feedback linearisation control

Since $M_{22} = m_2 l_{c2}^2 + m_3(l_{c3}^2 + l_2^2) + I_2 + I_3 + 2m_3 l_2 l_{c3} cos(\theta_3)$ from Equation (2) is always bounded away from zero over the configuration manifold, as a consequence of the uniform positive definiteness of the inertia matrix, $\ddot{\theta}_2$ can be derived from this Equation as:

$$\ddot{\theta}_2 = -M_{22}^{-1}(M_{21}\ddot{\theta}_1 + M_{23}\ddot{\theta}_3 + H_2 + G_2) \quad (4)$$

Further, substituting Equation (4) to Equations (1) and (3), the collocated feedback linearisation controller is derived and the original system of the WAcrobot is represented as:

$$\begin{aligned} \ddot{\theta}_1 &= v_1 & (5)\\ M_{22}\ddot{\theta}_2 + H_2 + G_2 &= -M_{21}v_1 - M_{23}v_3 & (6)\\ \ddot{\theta}_3 &= v_3 & (7) \end{aligned}$$

where v_1 and v_3 are the new control inputs as

$$\begin{aligned} v_1 &= \ddot{\theta}_1^r + k_1^d(\dot{\theta}_1^r - \dot{\theta}_1) + k_1^p(\theta_1^r - \theta_1) & (8)\\ v_3 &= \ddot{\theta}_3^r + k_3^d(\dot{\theta}_3^r - \dot{\theta}_3) + k_3^p(\theta_3^r - \theta_3) & (9) \end{aligned}$$

where $\theta_1^r(t)$ and $\theta_3^r(t)$ are reference trajectories and k_1^d, k_1^p, k_3^d and k_3^p are positive gains. These gains together with the initial condition, completely determine the particular trajectory of the zero dynamic to which the response of the complete system converges. Block diagram of the collocated feedback linearisation controller is illustrated in Figure 2. To excite the WAcrobot, from its pendent position, arctangent as function of velocity of second pendulum and sine function are employed for θ_3^r and θ_1^r, particularly $\theta_3^r = \alpha\, arctan(\dot{\theta}_2)$ and $\theta_1^r = a\, sin(\omega t)$ where α, a, and ω are constants. The arctangent function has the desirable characteristic of straightening out the first pendulum, allowing a balancing controller to catch the system in the approximately inverted position.

3.2 Non-Collocated Linearisation

In non-collocated linearisation, the passive DOF (θ_2) as well as the active DOF θ_1, as output $y = [\theta_1\ \theta_2]^T$ is linearised by nonlinear feedbacks. Equation (2) yields:

$$\ddot{\theta}_3 = -M_{23}^{-1}(M_{21}\ddot{\theta}_1 + M_{22}\ddot{\theta}_2 + H_2 + G_2) \quad (10)$$

where the condition $M_{23} = m_3 l_{c3}(l_{c3} + l_2 cos(\theta_3)) \neq 0$ is termed *Strong Inertial Coupling* and imposes some restrictions to the inertia parameters of the WAcrobot, namely that $l_{c3} > l_2$. Further, substituting Equation (10) to Equations (1) and (3), the non-collocated partial feedback linearisation controller is derived and the original system of the WAcrobot is represented as :

$$\begin{aligned} \ddot{\theta}_1 &= v_1 & (11)\\ \ddot{\theta}_2 &= v_2 & (12)\\ M_{23}\ddot{\theta}_3 + H_2 + G_2 &= -M_{21}v_1 - M_{22}v_2, & (13) \end{aligned}$$

where v_1 and v_2 are the new control inputs. Using the non-collocated linearisation method, a linear response from the second DOF (θ_2) can be achieved, even though it is not directly actuated but is instead driven by the coupling forces arising from motion of the third DOF (θ_3). If $\theta_1^r(t)$ and $\theta_2^r(t)$ are reference trajectories for θ_1 and θ_2, the input terms v_1 and v_2 may be chosen as:

$$\begin{aligned} v_1 &= \ddot{\theta}_1^r + k_1^d(\dot{\theta}_1^r - \dot{\theta}_1) + k_1^p(\theta_1^r - \theta_1) & (14)\\ v_2 &= \ddot{\theta}_2^r + k_2^d(\dot{\theta}_2^r - \dot{\theta}_2) + k_2^p(\theta_2^r - \theta_2) & (15) \end{aligned}$$

where k_1^d, k_1^p, k_2^d and k_2^p are positive gains. Similar to collocated feedback linearisation case, for θ_1^r and θ_2^r, the sine and arctangent functions are used.

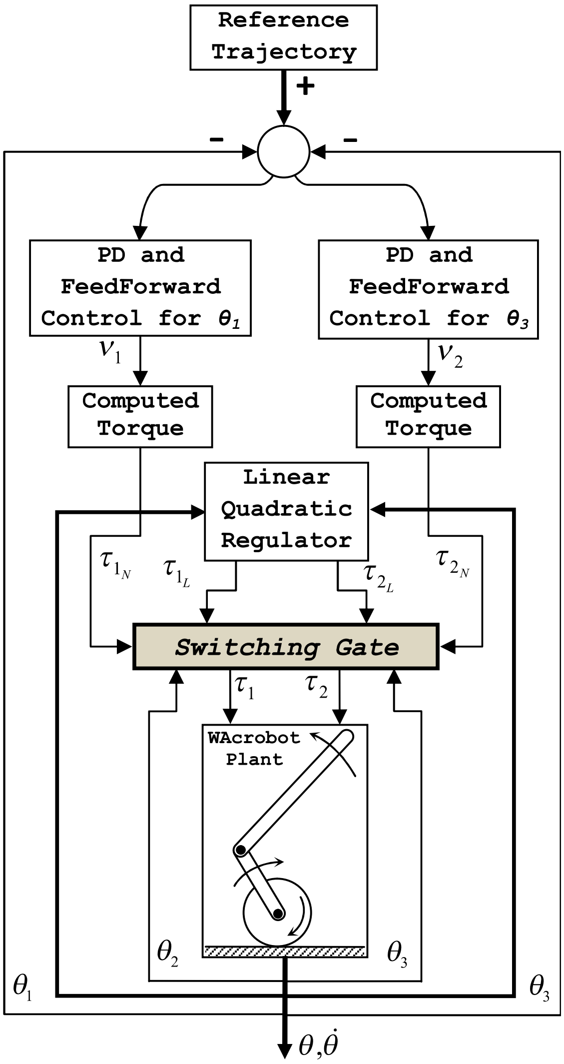

Fig. 3. Switching block diagram

4 MODE SWITCHING AND BALANCING

The controller supervisor excites the WAcrobot and forces the trajectories of pendulums to enter the basin of attraction of the local balancing controller and then smoothly switches to the balancing controller employed to maintain the WAcrobot inverted and to reject the possible external disturbance. The balancing controller is designed using the Linear Quadratic Regulator (LQR) based on the linearised plant model around the inverted equilibrium point. The LRQ is a controller for state variable feedback in such a way that $u = -Kx$ is the input so that the value of K is obtained from a minimizing problem of the functional cost

$$J = \int_0^\infty (x^{'}Qx + u^{'}Ru)dt$$

where matrix Q and R are positive semidefinite matrix and symmetric positive definite matrix which penalize the state error and the control effort, respectively. Figure 3 illustrates the switching block diagram from partial feedback linearisation controller to the balancing controller. In the proposed control system disturbances are handled by switching back into the swing-up mode and re-converging to the basin of attraction of the balancing controller. In this system, large disturbance can also be treated by switching to another linear controller for the nearest equilibrium point to the deviated position to keep the robot balanced there and then switching back again to the linear controller for the inverted position.

5 SIMULATION RESULTS

In order to verify the validity of the proposed method, numerical and visual simulations are carried out. The simulations are performed with the parameters given in Table 2.

Table 2. Parameters of the WAcrobot

Wheels/ Pendulums	Wheels	First Pendulum	Second Pendulum
m_i $[kg]$	1.22	0.28	0.72
l_i $[m]$	0.05	0.15	0.45
I_i $[kg.m^2]$	1.53E-003	5.98E-004	1.3138E-002

In table 2, parameter l for wheels means radius while this parameter for pendulums means length. The initial conditions for the WAcrobot while it is at rest in the pendent position are as

$$\theta_1 = 0 \quad \theta_2 = \pi \quad \theta_3 = 0$$
$$\dot{\theta}_1 = 0 \quad \dot{\theta}_2 = 0 \quad \dot{\theta}_3 = 0$$

and Q and R in the optimal regulator are chosen as $Q = diag([10, 100, 100, 0, 0, 0])$ and $R = diag([0.1, 0.1])$. By computing the LQR control law, the state-feedback gain matrix is obtained as:

$$K = \begin{bmatrix} 29.64 & -3.57 & -8.09 & -0.93 & -2.15 & -0.13 \\ 11.00 & 38.40 & 53.51 & 7.27 & 14.64 & 3.46 \end{bmatrix}$$

5.1 Collocated Linearisation

Figure 4 shows the simulation results for the swing-up of the WAcrobot using the collocated feedback linearisation controller. In this figure the simulation responses of angular position and velocity of the wheels and pendulums as well as applied torque to actuated DOFs are shown, respectively. In this simulation, controller gains are selected as $\alpha = 0.05$, $a = -2$, $\omega = 2$, $k_1^p = 20$, $k_1^d = 10$, $k_2^p = 10$ and $k_2^d = 5$ and the switching conditions to be met before changing from swing-up to balancing controller are determined by the following criteria:

$$\begin{aligned} ||\theta_2| - n\pi| &< 0.33, \ (n = 0, 2, ...) \\ ||\theta_3 - \theta_2| - n\pi| &< 0.27, \ (n = 0, 2, ...) \end{aligned}$$

which yields a suitable neighbourhood of the inverted position. As Figure 4 shows the switching conditions are satisfied and the swing-up phase is terminated at t = 0.96 s.

Figure 6 shows different snapshots of the visualised simulation of the swing- up and stabilisation of the WAcrobot. It is clear from both numerical and visualised simulations that the WAcrobot is swung up from its initial pendant position and is stabilised in the inverted position in less than 8 seconds. Note that both pendulums undergoes a complete rotations, but in different clockwise and counter clockwise directions.

5.2 Non-Collocated Linearisation

Considering the parameters in Table 2, the Strong Inertial Coupling condition is satisfied and the control law for the non-collocated linearisation can be utilised. The results of the swing-up simulation based on the non-collocated feedback linearisation controller using controller gains $\alpha = 0.05$, $a = 2$, $\omega = 2.5$, $k_1^p = 20$, $k_1^d = 10$, $k_2^p = 10$ and $k_2^d = 5$ and the switching criteria as

$$\begin{aligned} ||\theta_2| - n\pi| &< 0.25, \ (n = 0, 2, ...) \\ ||\theta_3 - \theta_2| - n\pi| &< 0.15, \ (n = 0, 2, ...) \end{aligned}$$

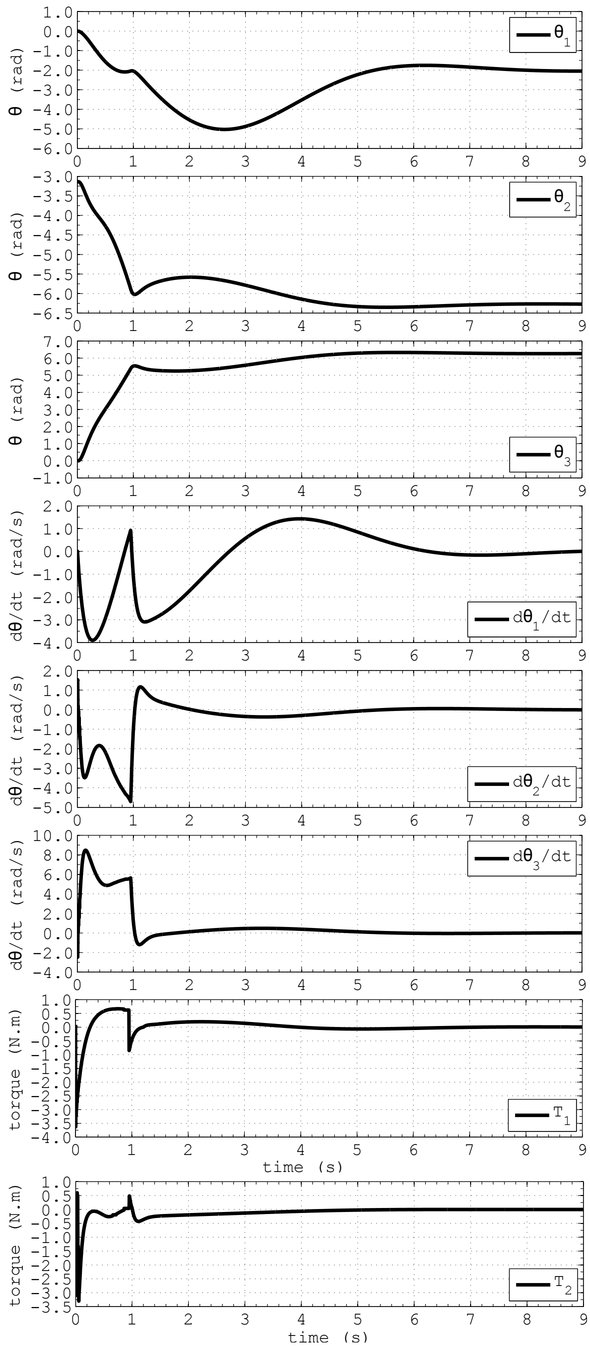

Fig. 4. The simulation responses of the wheels and pendulums using collocated feedback linearisation method

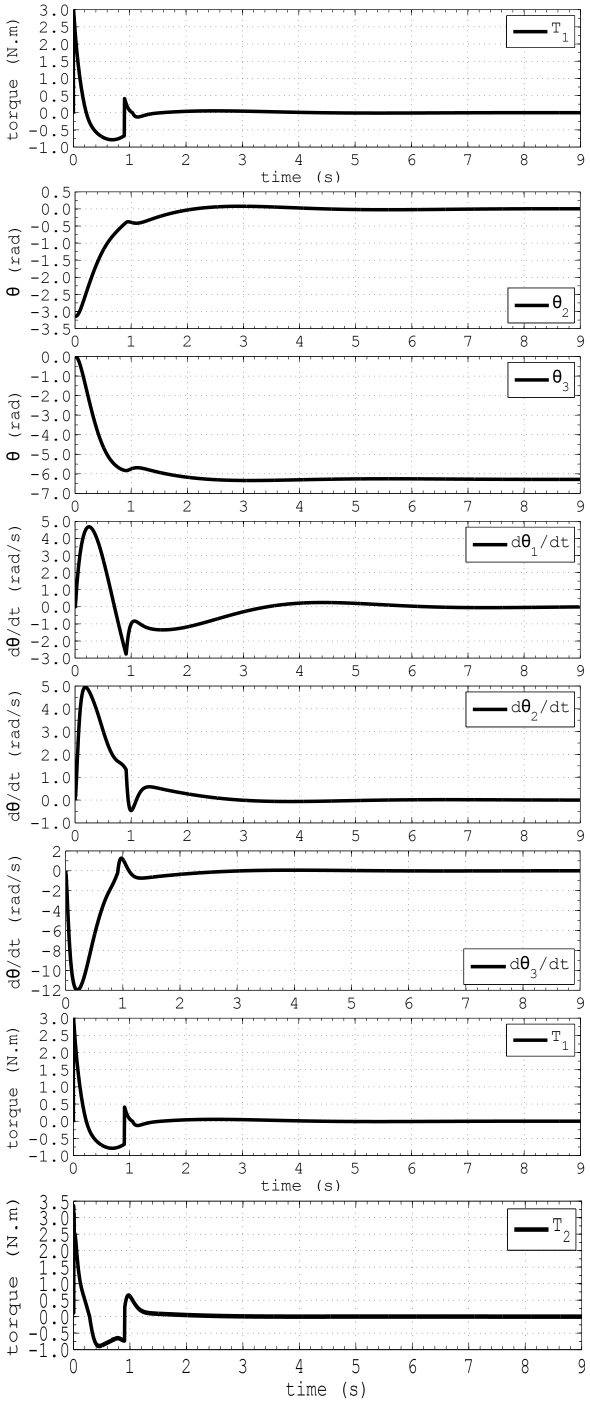

Fig. 5. The simulation responses of the wheels and pendulums angles and velocities as well as applied torque to actuated degrees of freedom using non-collocated feedback linearisation method.

are shown in Figure 5. Switching criteria are satisfied at time t=0.90 s. Various snapshots of the graphical simulation of the swing-up based on non-collocated linearisation are shown in Figure 7. It is concluded that, non-collocated linearisation controller, similar to the collocated linearisation controller, forces both pendulums to undergo one complete rotation from different directions, but the directions in collocated and non-collocated controller systems are reverse. Therefore, considering the mechanical specification of the WAcrobot, either of them can be chosen. The simulation results illustrate the effectiveness of the proposed control methodologies and the developed theories.

6 CONCLUSION

In this paper a novel underactuated mechanical system called WAcrobot, that is combination of Acrobot and mobile inverted pendulum, has been described. The swing-up control problem of the WAcrobot on the basis of switching control strategy is addressed. Collocated and non-collocated feedback linearisation methods have been evaluated to swing the WAcrobot up to any arbitrarily small neighbourhood of the upright equilibrium point. Balancing controller based on the LQR technique has been employed to stabilise it in the upright equilibrium point. This paper has also provided numerical and graphical simulation results to validate the obtained theoretical results and to demonstrate the correlation between the numerical results and the WAcrobot physical response. Good performance results have been obtained with the partial feedback linearisation and balancing controllers developed to swing up and stabilise the WAcrobot.

REFERENCES

[1] S.A. Campbell, S. Crawford, and K. Morris. Friction and the inverted pendulum stabilization problem. *Journal of Dynamic Systems, Measurement, and Control*, 130:0545021–0545027, 2008.

[2] F. Gordillo and J. Aracil. A new controller for the inverted pendulum on a cart. *International Journal of Robust and Nonlinear Control*, 18(17):1607–1621, 2008.

[3] W. Singhose, D. Kim, and M. Kenison. Input shaping control of double-pendulum bridge crane oscillations. *Journal of Dynamic Systems, Measurement, and Control*, 130:034504, 2008.

[4] K. Graichen, M. Treuer, and M. Zeitz. Swing-up of the double pendulum on a cart by feedforward and feedback control with experimental validation. *Automatica*, 43(1):63–71, 2007.

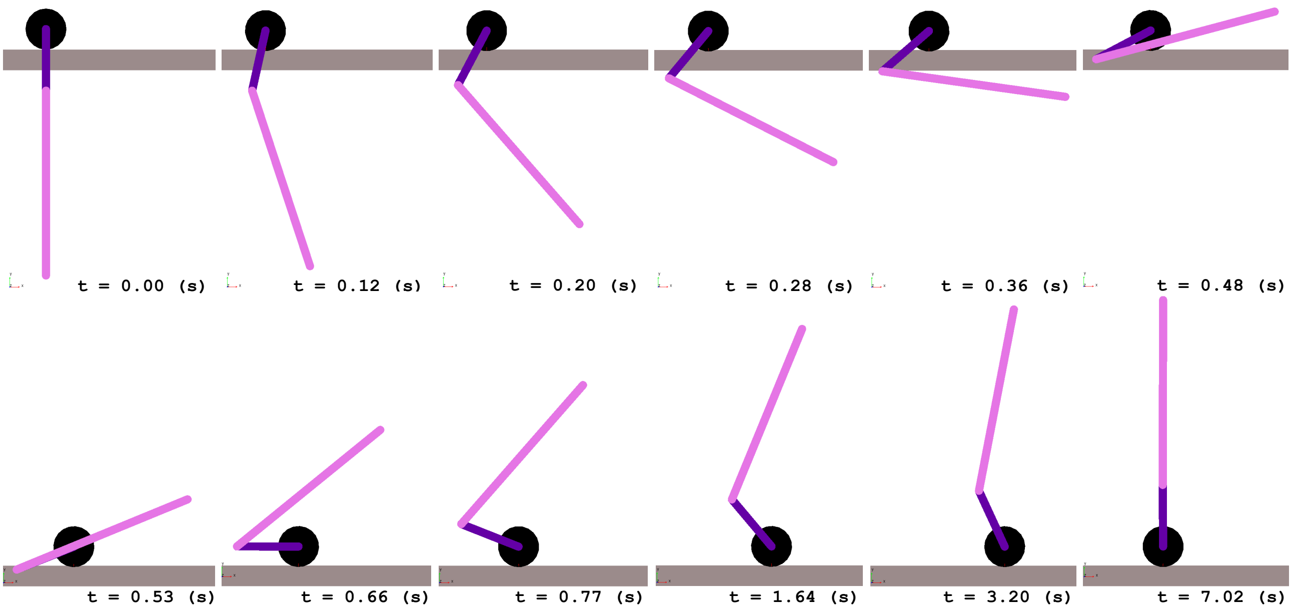

Fig. 6. Snapshots of the visualised simulation of the WAcrobot swinging up collocated feedback linearisation method

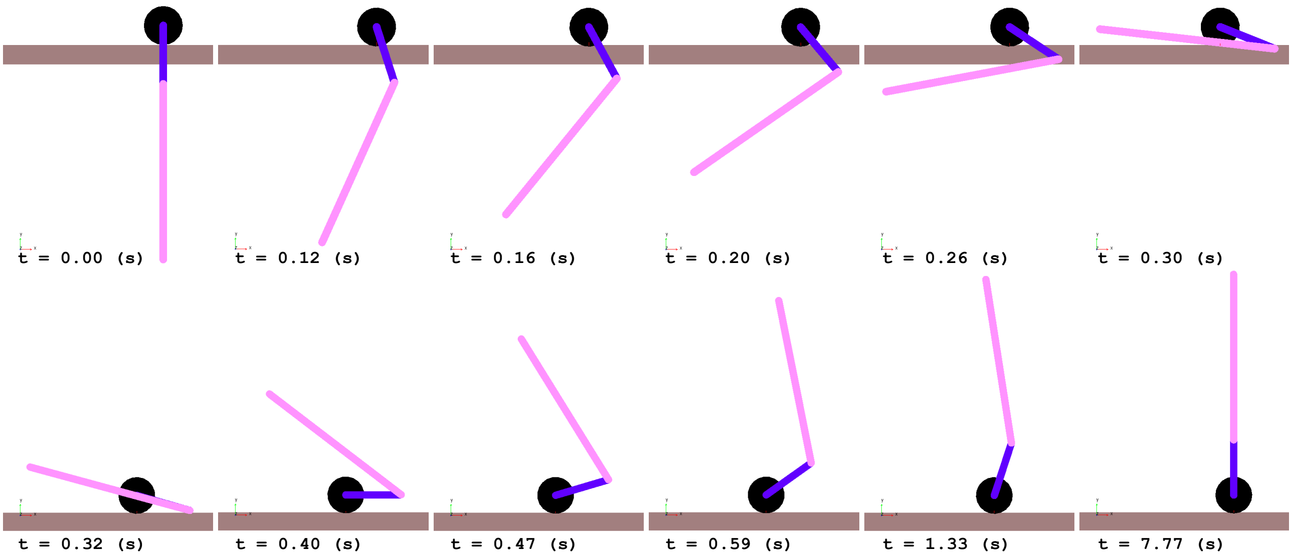

Fig. 7. Snapshots of the visualised simulation of the WAcrobot swinging up and stabilising using non-collocated feedback linearisation method

[5] I. Fantoni, R. Lozano, and MW Spong. Energy based control of the pendubot. *IEEE Transactions on Automatic Control*, 45(4):725–729, 2000.

[6] MW Spong. The swing up control problem for the acrobot. *IEEE Control Systems Magazine*, 15(1):49–55, 1995.

[7] X. Xin and M. Kaneda. Analysis of the energy-based swing-up control of the Acrobot. *International Journal of Robust and Nonlinear Control*, 17(16):1503–1524, 2007.

[8] S. Suzuki, K. Furuta, A. Sugiki, and S. Hatakeyama. Nonlinear optimal internal forces control and application to swing-up and stabilization of pendulum. *Journal of Dynamic Systems, Measurement, and Control*, 126:568, 2004.

[9] Y. Xu, M. Iwase, and K. Furuta. Time optimal swing-up control of single pendulum. *Journal of Dynamic Systems, Measurement, and Control*, 123:518, 2001.

[10] B. Castillo-Toledo, G. Obregón-Pulido, and O. Espinosa-Guerra. Structurally Stable Regulation for a Class of Nonlinear Systems: Application to a Rotary Inverted Pendulum. *Journal of Dynamic Systems, Measurement, and Control*, 128:922, 2006.

[11] S. Jung and J.T. Wen. Nonlinear model predictive control for the swing-up of a rotary inverted pendulum. *Journal of Dynamic Systems, Measurement, and Control*, 126:666–673, 2004.

[12] H. Hoang and M. Wongsaisuwan. Robust controller design for a rotary double inverted pendulum using linear matrix inequalities. In *Proceedings of the SICE Annual Conference*, pages 515–520, 2007.

[13] M.J. Anderson and W.J. Grantham. Lyapunov optimal feedback control of a nonlinear inverted pendulum. *Journal of Dynamic Systems, Measurement, and Control*, 111:554, 1989.

[14] S. Mori, H. Nishihara, and K. Furuta. Control of unstable mechanical system - Control of pendulum. *International journal of Control*, 23(5):673–692, 1976.

[15] K.J. AsstroKm and K. Furuta. Swinging up a pendulum by energy control. *Automatica*, 36:287–295, 2000.

[16] P.X. La Hera, L.B. Freidovich, A.S. Shiriaev, and U. Mettin. New approach for swinging up the Furuta pendulum: Theory and experiments. *Mechatronics*, 19:1240–1250, 2009.

[17] J. Searock, B. Browning, and M. Veloso. Turning segways into soccer robots. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004)*, volume 1, 2004.

[18] A. Salerno and J. Angeles. On the nonlinear controllability of a quasiholonomic mobile robot. In *Proceedings of the IEEE International Conference On Robotics And Automation*, volume 3, pages 3379–3384. IEEE; 1999, 2003.

[19] F. Grasser, A. D' Arrigo, S. Colombi, and A.C. Rufer. JOE: a mobile, inverted pendulum. *IEEE Transactions on industrial electronics*, 49(1):107–114, 2002.

[20] K. Pathak and S.K. Agrawal. Band-limited trajectory planning and tracking for certain dynamically stabilized mobile systems. *Journal of Dynamic Systems, Measurement, and Control*, 128:104, 2006.

[21] A. Salerno and J. Angeles. A new family of two-wheeled mobile robots: Modeling and controllability. *IEEE Transactions on Robotics*, 23(1):169–173, 2007.

[22] K. Pathak, J. Franch, and SK Agrawal. Velocity and position control of a wheeled inverted pendulum by partial feedback linearization. *IEEE Transactions on Robotics*, 21(3):505–513, 2005.

[23] K. Tsuchiya, T. Urakubo, and K. Tsujita. A motion control of a two-wheeled mobile robot. In *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (IEEE SMC'99)*, volume 5, 1999.

[24] J.C. Ryu, V. Sangwan, and S.K. Agrawal. Differentially Flat Designs of Underactuated Mobile Manipulators. *Journal of Dynamic Systems, Measurement, and Control*, 132:024502, 2010.

[25] M.M. Dalvand and B. Shirinzadeh. *Advanced Strategies for Robot Manipulators*, chapter Dynamic Modelling, Tracking Control and Simulation Results of a Novel Underactuated Wheeled Manipulator (WAcrobot), pages 91–106. InTech, 2011.

[26] M.W. Spong. Partial feedback linearization of underactuated mechanical systems. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, volume 1, pages 314–321, 1994.

Mohsen Moradi Dalvand received his Ph.D. from Monash University, Melbourne, Australia. He is currently a research fellow in Centre for Intelligent Systems Research (CISR) at Deakin University. He has published several papers in various international journals and conferences. His research interests include robotics, haptics, industrial automation, mechanical design engineering, motion study, and simulation. More information can be found in his web site at http://www.mrdv.org.

Bijan Shirinzadeh received engineering qualifications: Bachelors Degrees in Mechanical and Aerospace Engineering, and Masters Degrees in Mechanical and Aerospace Engineering from the University of Michigan, Ann Arbor Michigan, USA. He obtained PhD in Mechanical Engineering from University of Western Australia (UWA), Australia. He is currently a full Professor in the Department of Mechanical and Aerospace Engineering at Monash University, Australia. He is also the Director of Robotics & Mechatronics Research Laboratory (RMRL). His current research interests include mechanisms/robotics; mobile robotics and complex/autonomous systems; micro-nano manipulation mechanisms/systems; intelligent sensing and control; robotic-assisted minimally invasive surgery and micro-surgery; biomechatronics; and manufacturing and automation sciences.

Saeid Nahavandi received a Ph.D. from Durham University, Durham, U.K. He is an Alfred Deakin Professor, Chair of Engineering, and the Director of the Center for Intelligent Systems Research at Deakin University, Australia. He has published over 450 papers in various international journals and conferences. His research interests include modeling of complex systems, robotics and haptics. He is the Co-Editor-in-Chief of the IEEE Systems Journal, an Editor (South Pacific Region) of the International Journal of Intelligent Automation and Soft Computing. He is a Fellow of Engineers Australia (FIEAust), the Institution of Engineering and Technology (FIET) and Senior member of IEEE (SMIEEE).

AUTHORS' ADDRESSES

Mohsen Moradi Dalvand, Ph.D.
Saeid Nahavandi, Prof.
Centre for Intelligent Systems Research (CISR),
Deakin University,
Victoria 3216, Australia
e-mail: {mohsen.m.dalvand,
saeid.nahavandi}@deakin.edu.au

Bijan Shirinzadeh, Prof.
Department of Mechanical and Aerospace Engineering,
Monash University,
Victoria 3800, Australia
e-mail: bijan.shirinzadeh@monash.edu

Received: 2011-09-27
Accepted: 2013-02-26