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Adaptive Motion Control of Nonholonomic Intelligent Walker-Human Systems

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Abstract: This paper focuses on motion control of active intelligent walkers robust to system parameter variations and uncertainties. It presents a new realistic control-oriented model and, based on this model, an adaptive motion control design to generate appropriate torques to keep the i-walker in front of the user at the desired distance. Our control design utilizes inverse kinematics equations derived from a two-body kinematic model and to adaptively generate the reference velocities for maintaining ideal relative position of i-walker with respect to the user. The torques to track the reference velocities are generated using an adaptive proportional−integral−derivative control scheme, which is robust to unknown torque disturbances, combined with a computed torque based feedback linearization unit and a high gain observer to estimate the wheel velocities. The designed control scheme is formally analyzed and simulation tested for both symmetric and asymmetric gait patterns.

Keywords: adaptive control, physical human-walker interaction, least squares based parameter identifier, nonholonomic i-walker, feedback linearization, high gain observer

1. INTRODUCTION

Safety and stable motion are two required properties for intelligent walkers (i-walkers). In this regard, significant research has been conducted on motion control of various types of i-walkers in Hirata et al. [2005, 2007], Ko et al. [2013], Silva Jr. and Sup [2013], Cifuentes et al. [2014], Tan et al. [2011], Wang et al. [2012]. A set of kinematic and dynamic models have been developed for active and passive types i-walkers in Hirata et al. [2005, 2007], Ko et al. [2013], Silva Jr. and Sup [2013], Cifuentes et al. [2014], without considering the dynamic effects such as center of gravity (CG) shifts, load changes, friction, and dynamic uncertainties due to partial weight support. To address such dynamic variation and uncertainty issues, a limited number of adaptive controllers have been proposed for i-walkers with omni-directional wheels in the literature, Tan et al. [2011], Wang et al. [2012]. However, all these studies neglect the fact that the physical human-walker interaction (pHWI) is not only dependent on the user weight but also the user gait dynamics and characteristics.

The main contributions of this paper are development of a nonholonomic i-walker-human system model taking into account users with symmetric and asymmetric gait dynamics and characteristics, and thus the model is more comprehensive and realistic for human-walker motion, and design of an adaptive motion control scheme to make the system robust to load changes and the user steering characteristic for providing safe, stable, and efficient human-walker motion. To design a practically implementable controller, different from the existing literature, where wheel velocities of the i-walker are directly obtained using tachometers or estimated by observers based on i-walker kinematic models as in Huang et al. [2014], we use the system dynamic model to estimate the wheel velocities.

As the high-level layer of the control scheme, an inverse kinematic controller in Cifuentes et al. [2014] is utilized to produce desired i-walker velocities based on the user motion relative to the i-walker, which is called the user motion intention. To generate the required torques for tracking these desired velocities, a proportional−integral−derivative (PID) control scheme is designed such that the closed loop system is robust to constant torque disturbances due to unknown friction forces, i-walker CG displacement and load changes. The PID control scheme is combined with feedback linearization unit based on computed torque control approach, and a high gain observer (HGO) to estimate the wheel velocities, robustly to sensor noises. Lastly, an adaptive version of developed dynamic controller is proposed, utilizing an on-line least squares based parameter identifier estimating the unknown system parameters. The proposed adaptive control scheme is simulation tested and compared for both users.

The paper is organized as follows. Section 2 is dedicated to analysis of the effect of pHWI on the i-walker dynamics. In Section 3, control-oriented kinematic and dynamic models of the i-walker-human user system are derived. Designs of the base robust motion control scheme, state estimator, the parameter estimation, and adaptive PID design scheme are presented in Sections 4, 5, and 6, respectively. Section 7 presents the simulation results to verify the designs and analyze their characteristics. Final, conclusions of the paper are given in Section 8.

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2. HUMAN EFFECT ON THE INTELLIGENT WALKER DYNAMICS

I-walker physically interacts with the upper limbs of the user as seen in Fig. 1. This pHWI affects the dynamics of the i-walker due to the applied forces by the user on the i-walker handles during human-walker motion. The pHWI in the sagittal plane (x-z plane) can be described as

$$\begin{aligned} F_x &= R_x - m_h \ddot{x}_h, \\ F_z &= m_h(\ddot{z}_h - g) - R_z, \\ F_z c &= R_z b \end{aligned} \tag{1}$$

where x_h, z_h denote the location of the human CG in the x and z axes, respectively. m_h refers to human mass. Human CG location is the function of the human joint angles. R_x and R_z are the total ground reaction forces (GRFs) in the directions of x and z axes. b and c are the distances of human CG to GRFs and to the walker handles in x-axis, respectively. (1) implies that in addition to the user body weight and body pose, the total vertical force F_z is also dependent on the user CG motion and GRFs which have periodic nature. It can be concluded that while the total load on the i-walker is periodically changing with human CG motion in the sagittal plane, the load distribution between the handles shows periodic changes with the horizontal motion of human CG in the frontal plane (in y-axis) and human gait phase during walking as in Alwana et al. [2007], Abellanas et al. [2010].

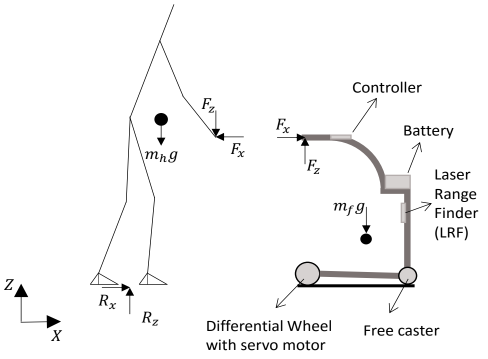


Fig. 1. Free body diagrams of human and i-walker in the sagittal plane.

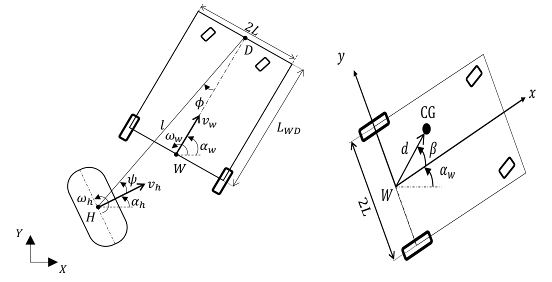
Houglum and Bertoti [2012] states that the human CG displacement is closely related to the gait parameters, such as swing phase, stance phase, stride length, step width and walking speed. This implies that the user gait pattern determines the load distribution on the i-walker during walking.

In this paper, the i-walker CG displacements and the load changes on the i-walker due to pHWI based on gait dynamics and characteristics are considered to achieve more comprehensive dynamic model. This dynamic model can be used to take into account both types of users in controller designs for i-walker-human systems to better generate the required torques for stable human-walker motion.

3. STRUCTURE AND DYNAMIC MODELLING OF INTELLIGENT WALKER

The i-walker configuration studied in this paper consists of a support frame with controller, battery and LRF, two differential powered wheels and two free casters as shown in Fig.1.

3.1 Kinematic Modelling



(a) Human-walker motion kinematic model. (b) Proposed dynamic model of the i-walker.

Fig. 2. Kinematic and dynamic models of the i-walker.

The kinematic model of human-walker motion is based on that in Cifuentes et al. [2014], and illustrated in Fig. 2a. The nonholonomic i-walker motion is driven by two independent motors mounted at rear wheels of radius r. These wheels are separated by distance $2L$. L_{WD} is the distance between the point W and the point D.

The variables, v, ω, and α represent linear velocity, angular velocity, and orientation, respectively. The parameters for the human are described with the subscript h, whereas the walker parameters are denoted by the subscript w. Kinematic parameters l, ψ, and ϕ of human-walker relative motion are defined as the distance between the points D and H, the angle between v_h and l, the angle between l and the longitudinal axis of i-walker, respectively.

The location of the i-walker in the reference frame is defined by the vector $p_w = [x_w, y_w, \alpha_w]^T$ where (x_w, y_w) and α_w are the coordinates of point W and the heading angle, respectively. Choosing $q = [x_w \; y_w \; \alpha_w \; \theta_R \; \theta_L]^T$ as the generalized coordinate vector, the forward kinematic model of the i-walker is obtained as follows:

$$\dot{q} = S(q)\dot{\eta}, \quad S(q) = \begin{bmatrix} r\frac{1}{2}\cos\alpha_w & r\frac{1}{2}\sin\alpha_w & r\frac{1}{2L} & 1 & 0 \\ r\frac{1}{2}\cos\alpha_w & r\frac{1}{2}\sin\alpha_w & -r\frac{1}{2L} & 0 & 1 \end{bmatrix}^T \tag{2}$$

where $\eta = [\theta_R \; \theta_L]^T$ is the rotational displacements of the right and left wheels with the radius of r.
There exist three constraint equations in the kinematic model of the i-walker, which are based on two assumptions: (i) no lateral slip, and (ii) pure rolling motion. The constraint equations, detailed in Sarkar et al. [1992], can be written in the matrix form as follows:

$$A(q)\dot{q} = 0, \quad A(q) = \begin{bmatrix} -\sin\alpha_w & \cos\alpha_w & 0 & 0 & 0 \\ \cos\alpha_w & \sin\alpha_w & L & -r & 0 \\ \cos\alpha_w & \sin\alpha_w & -L & 0 & -r \end{bmatrix}. \tag{3}$$

The time derivative of (2) is

$$\ddot{q} = \dot{S}(q)\dot{\eta} + S(q)\ddot{\eta}. \tag{4}$$