Passive Gait Synchronization of Human-Robot Systems Using a Dynamically Coupled Double Rimless Wheel Model*

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I. INTRODUCTION

The Extra Robotic Legs (XRL) system is a robotic augmentation worn by a human operator consisting of two articulated robot legs that walk with the operator and help bear a heavy backpack payload. When walking together, the human-XRL system forms a type of quadrupedal system (See Fig. 1-a). Unlike fully biological or fully robotic quadrupeds, the human-XRL system consists of two independently controlled biped systems which are physically connected. Synchronizing the human-gait system is challenging because there is no centralized controller to command the entire quadruped. Our goal is to establish a natural regulator that achieves a desired gait cycle by exploiting the intrinsic dynamic synchronization properties of the human-XRL system.

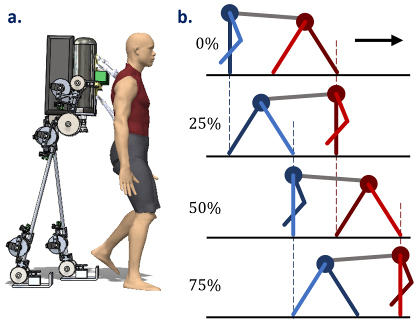

Fig. 1: The Extra Robotic Legs System and desired gait cycle, with the hind legs leading the rear legs by 25%. This quadrupedal system behaves as if it were two coupled bipeds.

This desired gait cycle is informed by animal biomechanics. Analysis of quadrupedal animal gaits [2] shows that quadrupeds behave as if they were two coupled bipeds and tend to fall into a gait cycle where the hind limbs lead the fore limbs by about 25% of the stride time (or 90° out of phase) during steady-state walking, as shown in Fig. 1-b. This walking gait cycle has also been found to maximize the margin of stability of the quadruped's balance [3]. It has also been shown that gaits with more sequenced collisions per stride are more energy efficient than gaits which group multiple foot collisions together [4]. It is of interest, then, to analyze how intrinsic dynamics can lead the Human-XRL System to naturally fall into this special gait cycle. **In this work we present a dynamic model and a preliminary experiment that captures this passive gait synchronization for the human-XRL system.**

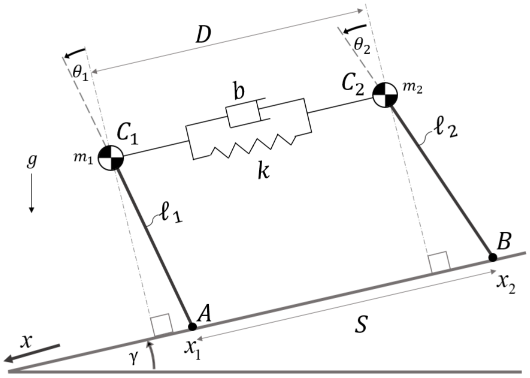

Fig. 2: The Coupled Rimless Wheels Model

II. THE DYNAMICALLY COUPLED DOUBLE RIMLESS WHEEL MODEL

The canonical Rimless Wheel model [5] is a simple nonlinear hybrid-dynamic model that captures natural bipedal walking dynamics. In order to explore the effects of dynamic coupling in a quadrupedal system, we extend the model by adding a second Rimless Wheel and connecting the two with a passive coupler made up of a spring k and a viscous damper b in parallel. See Fig. 2.

The masses m_1 and m_2 of each pendulum are point masses atop massless links of length ℓ_1 and ℓ_2, respectively. The angle of the first Rimless Wheel about point A is θ_1 and the angle of the second about point B is θ_2, and the step angles for each are α_1 and α_2. The distance between the coupler endpoints is D and the unstretched length of the spring is D_0.

The nonlinear state equations during the continuous dynamics are, assuming $\ell_1 = \ell_2 = \ell$ and $m_1 = m_2 = m$:

$$\begin{aligned}\ddot{\theta}_1 = \frac{g}{\ell}\sin(\theta_1+\gamma) - \frac{k}{m\ell}(D-D_0)\cos(\theta_1+\beta)\\ -\frac{b}{m}\Big(\cos(\theta_1+\beta)\dot{\theta}_1 - \cos(\theta_2+\beta)\dot{\theta}_2\Big)\cos(\theta_1+\beta)\end{aligned} \tag{1}$$

$$\begin{aligned}\ddot{\theta}_2 = \frac{g}{\ell}\sin(\theta_2+\gamma) + \frac{k}{m\ell}(D-D_0)\cos(\theta_2+\beta)\\ +\frac{b}{m}\Big(\cos(\theta_1+\beta)\dot{\theta}_1 - \cos(\theta_2+\beta)\dot{\theta}_2\Big)\cos(\theta_2+\beta)\end{aligned} \tag{2}$$

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