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.

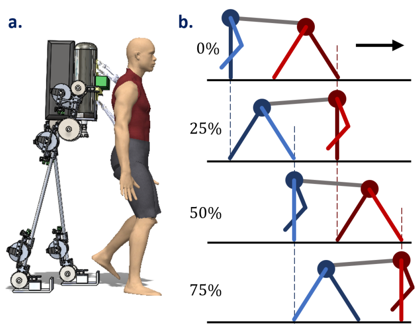

Fig. 1: The Extra Robotic Legs System and desired gait cycle, with the hind legs leading the rear legs by 25%. This quadrupedal system behaves as if it were two coupled bipeds.

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.**

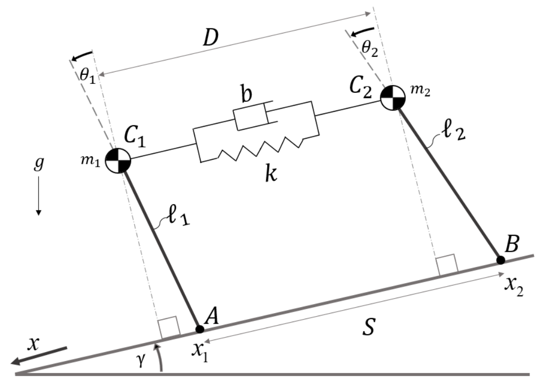

Fig. 2: The Coupled Rimless Wheels Model

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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$$\dot{D} = \ell \left(\cos(\theta_1 + \beta)\dot{\theta}_1 - \cos(\theta_2 + \beta)\dot{\theta}_2 \right) \tag{3}$$

where, for brevity, we write the coupler angle as

$$\beta = \sin^{-1} \left(\frac{\ell}{D} (\cos\theta_1 - \cos\theta_2) \right) \tag{4}$$

and the state of the system can be fully determined with the following state vector

$$x = \begin{bmatrix} \theta_1 & \dot{\theta}_1 & \theta_2 & \dot{\theta}_2 & D \end{bmatrix}^T \tag{5}$$

The hybrid heel strike/toe-off dynamics are treated independently for each pendulum system at the angle limit α of forward lean before the swing leg impacts and becomes the new stance leg, following with the canonical Rimless Wheels model.

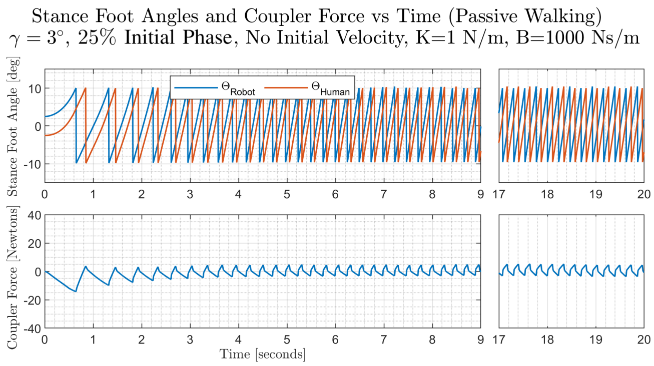

Fig. 3: Passive walk with initial phase difference of 25% converges to the desired 50% difference

Because the Coupled Rimless Wheels system has a straightforward state-space representation, it can be simulated using an ODE solver. Fig. 3 shows the case where the initial phase difference between the human and the robot is 25% out of phase. As the human and robot walk down the slope, the phase difference shifts and converges to the desired 50%. If we design the robotic XRL system to behave like a rimless wheel when walking, we can expect that connecting it to the human via the proper spring-dashpot can naturally lead the whole system to converge to the 25% out-of-phase 4-legged gait cycle.

III. Experimental Validation of Passive Coupled Rimless Wheel Convergence to Gait Synchronization

A prototype Coupled Rimless Wheels system was built in order to test gait cycle convergence between two passive dynamic walkers (See Fig. 4). Each wheel was designed to be human-sized with $\ell = 0.9652$ meters (38 inches) which is the center of mass for a 1.7272 meter (5 foot 8 inch) tall male. Twelve spokes give each wheel a step angle $\alpha = 15°$. The coupler consists of a spring and a dashpot constrained to be loaded only linearly. The damper was tuned to be roughly 100 [Ns/m] and the coupler spring was chosen to be 5.25 [N/m].

The Coupled Rimless Wheels were sent down a gentle slope of $\gamma = 2°$ while a camera on a tripod filmed the result

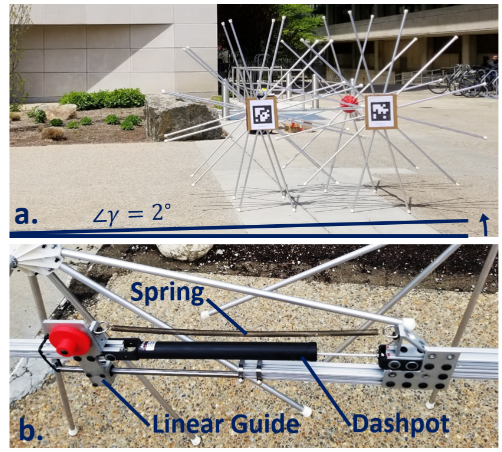

Fig. 4: Setup for testing synchronization of a Coupled Rimless Wheels system using a hardware-implemented coupler.

from the left side. Fig. 5 shows the trajectory of the Rimless Wheels and the normalized angle difference $\phi = \theta_1 - \theta_2$ for the first 5 seconds of Experiment . While ϕ is oscillatory, it converges to within $\pm 2°$ of the desired angle difference of $15°$ within several steps. This result demonstrated that two coupled walking systems can synchronize their gaits through passive means alone.

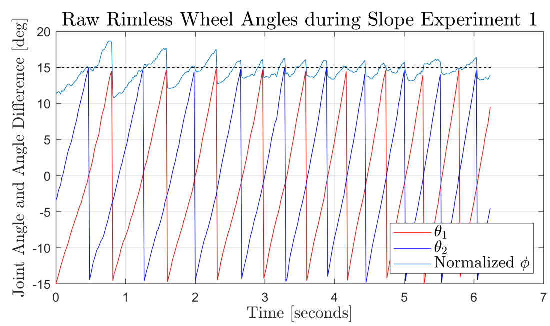

Fig. 5: θ_1, θ_2, and ϕ during Experiment Trial 1 shows synchronization of the physically implemented system to the desired gait cycle within 7 steps.

References

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