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# ROBOTRIKKE: DESIGN, MODELING AND EXPERIMENTATION WITH A ROBOTIC TRIKKE.

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## ABSTRACT

*In this paper we present new experimental results for a novel underactuated system called the* ROBOTRIKKE. *The* ROBOTRIKKE *is a three-wheeled system that can be driven by periodic motion of its front steering wheel combined with rocking side-to-side motion of a robotic rider. We present two new generations of the* ROBOTRIKKE *including a ABS model made using Shape Deposition Manufacturing (SDM). We present modeling, simulation and experimental results for gait generation for the* ROBOTRIKKE *using a combination of periodic inputs for the steering axis and a rider. We show how a rocking motion (as used by human riders) can be used to improve the performance of the* ROBOTRIKKE.

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## 1 Introduction

The TRIKKE (Fig. 1) is a three-wheeled human-powered scooter produced by **Trikke Tech Inc**. It can be propelled by a single rider using a combination of swaying and cyclic inputs to the steering axis. The rider's feet never move from fixed footrests on the TRIKKE, and do not come into contact with the ground. Thus there is no *pushing off* unlike in riding a skateboard or rollerblading. The rider starts out by turning the steering axis from side to side. The TRIKKE then starts moving in a sinusoidal manner. The motion then progresses with the rider *rocking* the steering axis from side to side. The motion can be further complemented by an appropriate weight transfer onto different feet corresponding to the direction in which the TRIKKE is instantaneously turning. The TRIKKE can achieve a speed of 18 mph on flat ground.

Systems using undulatory locomotion techniques have been widely studied in the recent past. This includes systems like the Snakeboard [1], the Variable Geometric truss [2], the Roller Racer [3], the Roller Walker [4], [5] and the ROLLERBLADER [6] and various snake-like robots [7]. In contrast to more conventional locomotion using legs or powered wheels, these systems rely on relative motion of their joints to generate net motion of the body. The joint variables or *shape* variables, are moved in cyclic patterns giving rise to periodic shape variations called *gaits*. A salient feature of these systems is the presence of multiple *nonholonomic constraints* similar to the TRIKKE.

Henceforth, we will refer to the commercially available version of the system as the TRIKKE and to our robotic version of this system as the ROBOTRIKKE. In earlier work [8] with the first-generation of the ROBOTRIKKE, we had presented a controller for following a straight line trajectory using only the steering input for the ROBOTRIKKE. We also contrasted our work with that for the Roller-Racer in [3]. The new generation of the ROBOTRIKKE that we present here differs from the Roller-Racer in two salient features:

1. The Roller-Racer has a vertical steering axis while the ROBOTRIKKE has a tilted steering axis and a steering arrangement more like that of a bike.
2. The ROBOTRIKKE system has an extra degree of freedom: the ability of the rider to swing from side to side.

In this paper, we explore design, modeling and control of the ROBOTRIKKE. We model the unique front-steering axis and joint for the ROBOTRIKKE. We use Shape Deposition Manufacturing (SDM) to manufacture prototypes of the ROBOTRIKKE. In [8], we had actuated the earlier prototype of the ROBOTRIKKE with a single rotary input at the steering. Here, we also incorporate the model of a rider and examine the effect a rider can have on the ROBOTRIKKE. *It should be noted that the TRIKKE's motion is dynamic and hence it is not possible to explain the motion of the TRIKKE using just kinematics*.

The dynamic model of the ROBOTRIKKE is closely related to the model of a bike. In our previous work [9], we explained how a rider is able to balance the bicycle while propeling it forward using a periodic input for the steering. In this work, because the ROBOTRIKKE is a three-wheeled system, balancing the system is not required. The rear platform of the ROBOTRIKKE is also much heavier than the front and so the center of gravity of the robot is always within the triangle of support formed by the three wheels for all motions we have experimented with. An appropriate choice of input for the rider allows the system to travel at greater speeds as is observed in the motion of the actual TRIKKE - the rider plays a critical part in actuating the system. We present theoretical and experimental results with the robots to show the effect of a rider on the system.

The organization of this paper is as follows. In Section 2, we briefly present design details for the newest generations of the ROBOTRIKKE. In Section 3, we present the model for the ROBOTRIKKE. The model includes a rider on the robot. In Section 4, we present simulation results for different kinds of inputs for a simplified model of the ROBOTRIKKE and experimental results for the multiple generations of our robot and also for a version with a swinging weight mounted on the platform (to model the effect of a human rider).

Figure 1. The commercial TRIKKE.

## 2 Design of the ROBOTRIKKE

Our first prototype for the ROBOTRIKKE was a simple model with a single rotary steering joint [8]. Thus, no out of plane motion was possible for the prototype. However, the original TRIKKE has a joint arrangement that allows the front steering handle to roll from side to side (Figure 2). This is achieved by constrained motion about a set of perpendicular axes ($a_1$ and $a_2$). The joint allows the left and right rear platform to independently rotate about axis $a_1$ while a coupling link rotating about axis $a_2$ and restricted by the rubber sleeve shown in Figure 2 couples the motion of the two platforms relative to each other. This joint allows the rear wheels to stay in contact with the ground when the front handle is *rocked* in this manner from side to side. The geometry of this joint ensures that the motion is limited and the system is stable. This motion cannot be achieved on our earlier prototype. We now present the design for two prototypes where a combination of materials of different flexibility was used to generate this kind of motion of the joint.

### 2.1 Prototype I

To be able to achieve motion similar to that of the TRIKKE, the joint attaching the steering platform to the rear platforms of the TRIKKE was redesigned. Figure 4 shows the resultant joint designed to attach the steering platform to the rear platform of the robot. The joint allows the two legs of the rear platform to move up and down and twist from side to side. This approximates the corresponding motion of the original TRIKKE model. It allows the front steering platform to rock from side to side and the rear platforms to move in concert with the front platform. The cross

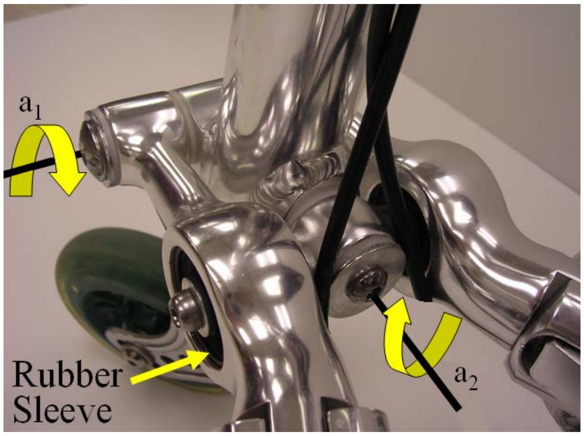



Figure 2. The joint for the steering handle of the TRIKKE.

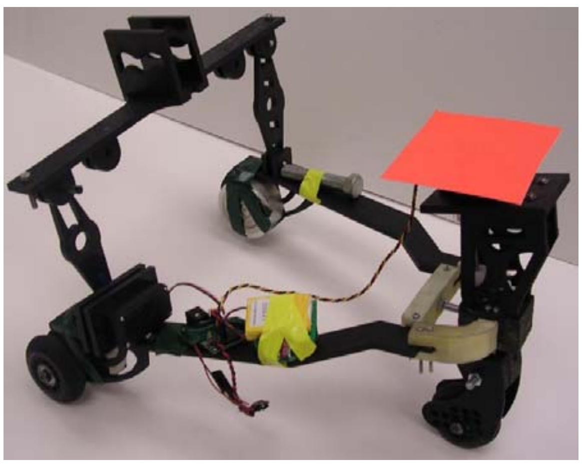


Figure 3. The first prototype for the ROBOTRIKKE platform.

beam couples the two legs of the rear platform and prevents large relative motion between the two legs. A metal *coupling pin* attaching the steering platform to the cross beam restricts the bending of the rear platform up and down. The complete prototype is shown in Figure 3.

The joint designed for this prototype performed very well in experiments and exhibited the desired characteristics. In addition to building this prototype, we also explored the use of a rapid prototyping technique known as shape deposition manufacturing (SDM) to build an additional prototype.

### 2.2 Shape Deposition Manufacturing: Prototype II

Shape Deposition Manufacturing (SDM) is a useful prototyping technique for creating multi-material and multi-layer parts. It is a solid freeform fabrication process which systemically combines material deposition with material removal

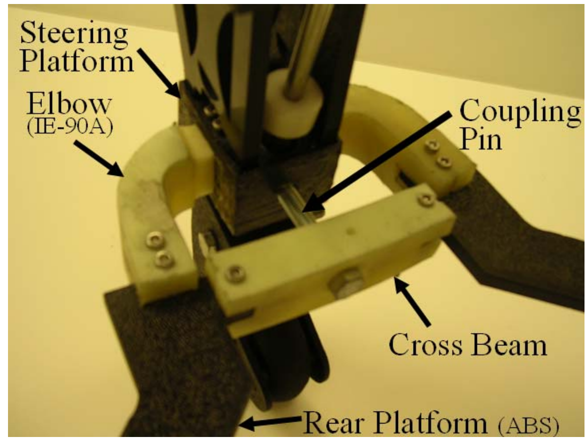



Figure 4. The joint for the steering handle of the ROBOTRIKKE.

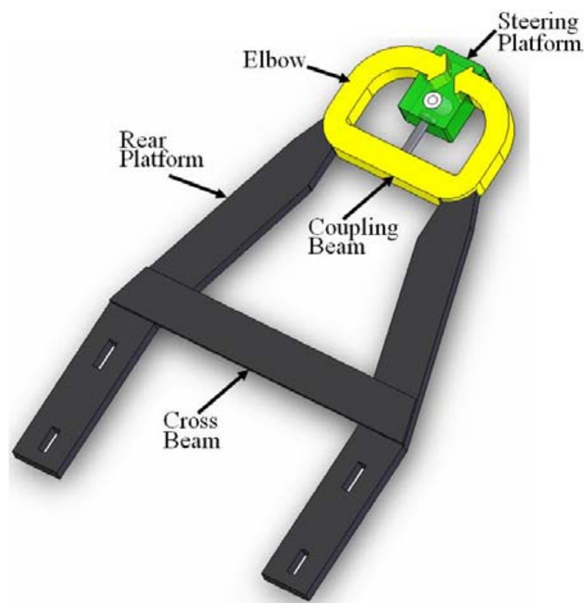



Figure 5. The SDM prototype for the ROBOTRIKKE platform.

processes. The general SDM design principles and techniques are covered in detail [10], and have been applied to robotics [11,12]. We present here only a brief description of the use of this technique to build the newer prototype of the ROBOTRIKKE.

For the fabrication of the ROBOTRIKKE frame, the SDM process offered the advantage of creating a balanced monolithic frame. A precision CNC-milled mold used for creating the platforms reduced misalignment problems. Using the observed behavior of the previous prototype as a reference, the new prototype was created using a combination of polymers with different modulii of elasticity. The steering shaft guide, which is a hollow tube of Teflon, and an aluminum coupling pin were directly em-

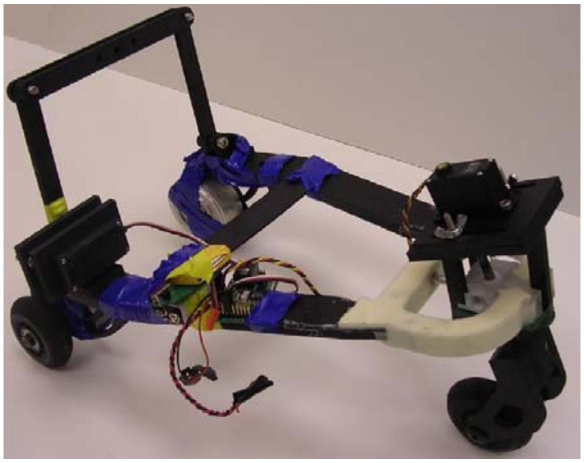


Figure 6. The SDM based prototype of the ROBOTRIKKE.

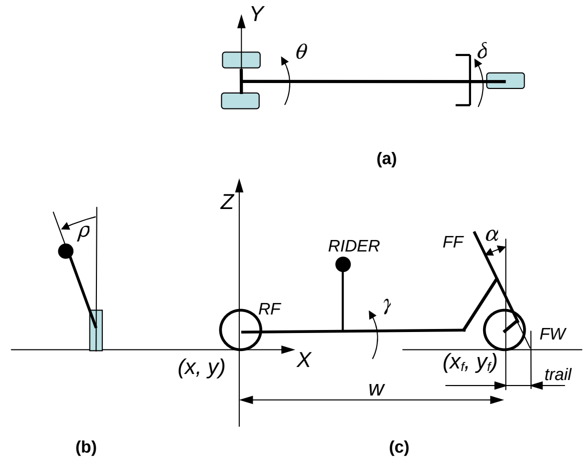



Figure 7. The Trikke model used for analysis.

bedded in the polymer used to create the steering platform. The rear platforms were made from ABS and also embedded into the softer joint material used to create the joint between the steering platform and the rear platform. Arrow-shaped pockets were milled out of the steering platform to improve the bond strength of the elbows with the steering platform. An additional cross-beam was added at the back of the finished model to limit the relative motion of the two legs of the rear platform. Tests proved that the elbows provided adequate stiffness and flexibility for the frame. Under torsion, the elbows replicate the limited rotation that is found on the TRIKKE. A solid model of the final platform (combination of rear and steering platforms) is shown in Figure 5. The finished prototype is shown in Figure 6.

## 3 TRIKKE Dynamics

The dynamics of the TRIKKE system are modeled using the classical Lagrange-d'Alembert equations. More details on the use of these equations can be found in our earlier work [8]. In this section, we will present a dynamic model for the ROBOTRIKKE.

### 3.1 TRIKKE Model

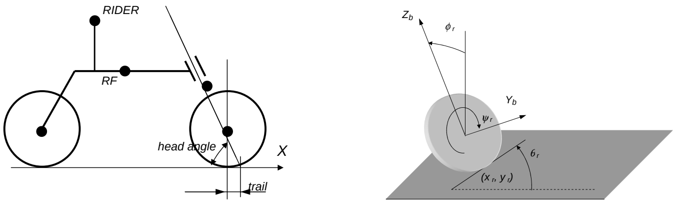
A side and top view of the model for the TRIKKE is shown in Fig. 7. The system consists of a steerable front wheel and two back wheels. When steering forward, the point of intersection of the steering axis with the ground is in front of the contact point $(x_f, y_f)$ of the front wheel with the ground. This is similar to the steering arrangement for bicycles in Fig. 8(a). The steering arrangement for a bicycle helps ensure stability of the zero steering position, i.e. the position in which the steering angle $\delta = 0$, when the bicycle is moving.

To simplify the dynamic analysis of the system, we make a few assumptions. When the ROBOTRIKKE rolls from side to side, one of the rear wheels would come out of contact with the ground if the rear platform were attached to the front steering platform using only a single rotary joint. Instead, in the actual TRIKKE, the rear platform is attached to the front platform using a combination of rotary joints. This allows the front steering platform and the rider to roll from side to side while ensuring the rear wheels stay on the ground. As noted earlier in Section 2, the joint design for the ROBOTRIKKE ensures the same effect. Based on the design of the prototype, we make the simplifying assumption that the rear platform does not roll from side to side. This assumption is justified since the design of our prototype ensures the rear wheels stay on the ground while the out of plane motion of the rear platform does not have significant effects on the dynamics of the system.

Further, as shown in Fig. 7(a), the steering handle has only one degree of freedom $\delta$. This angle, henceforth referred to as the steering angle, is actuated using a torque $\tau_\delta$ applied to the handle bars similar to that applied by a bicycle rider to turn the handlebars of a bicycle.

We divide the system into a set of five distinct rigid bodies: the rear platform, rear set of wheels (which we will model as a single component), the front frame, the front wheel and the rider. The configuration space for the rear wheel of the TRIKKE is represented by $SE(2)$. In the global frame, the position $(x, y)$ of the TRIKKE is characterized by the position of point of contact of the rear wheel with the ground. The orientation $\theta$ of the TRIKKE is the orientation of the rear wheel with respect to an inertial reference frame. The steering angle $\delta$ is the angle through which the handle bars have been turned. The pitch $\gamma$ is the pitch angle for the rear platform.

The steering axis is attached to the TRIKKE at an angle $\alpha$ as shown in Fig. 7(c). A wheel of radius $R_{fw}$ is attached to the end of the steering axis. As shown in Fig 9, when the steer-




(a) A sketch of a bicycle. (b) A rolling, falling disc.

Figure 8. Modeling the ROBOTRIKKE: Related systems

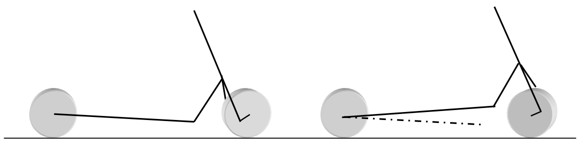


Figure 9. Turning the steering axle affects the pitch of rear platform.

ing handle is turned, the rear platform of the TRIKKE will pitch up and down, i.e. the pitch angle of the rear platform $\gamma$ is related to the steering angle $\delta$. The front wheel is represented as a *rolling falling disk* (Fig. 8(b)) with generalized coordinates $(x_f, y_f, \theta_f, \phi_f, \psi_f)$. The inertia and geometric parameters of the model of the ROBOTRIKKE used for analysis are presented in Table 1.

A detailed dynamic analysis of the ROBOTRIKKE has been presented in [8] and is not repeated here for brevity. The effect of a rider on the system was briefly presented in that work, but here we present experimental results to examine the effect of rider motion on the robot. The rider is modeled as a point mass and has a single degree of freedom. The rider is able to roll from side to side as shown in Fig 7. Further, we assume the existence of an actuator that provides the necessary torque $\tau_\rho$ for rolling the rider (here $\rho$ is the lean angle for the rider).

The complete set of generalized coordinates for the ROBOTRIKKE is given by $q = (x, y, \theta, \psi_r, \gamma, \delta, x_f, y_f, \theta_f, \phi_f, \psi_f, \rho)$ where $\psi_f$ and $\psi_r$ represent the angular rotations of the front and rear wheels about their axles respectively.

The constraints acting on the system can be represented as:

$$A(q)\dot{q} = 0. \tag{1}$$

Now, we choose an appropriate basis for the nullspace of $A(q)$ so that the allowable velocities for the system are given by

$$\dot{q} = \Gamma \dot{q}_d. \tag{2}$$

Here, the columns of $\Gamma$ are the basis vectors for the nullspace of $A(q)$ and the $\dot{q}_d$'s represent an appropriate choice of independent speeds for the system.

Now, using the Lagrange-d'Alembert equations (a detailed derivation is presented in [8]), we can write the dynamic equations of the system as,

$$\tilde{M}\ddot{q}_d + \tilde{C}(q)[\dot{q}_d, \dot{q}_d] + \tilde{N}(q, \dot{q}_d) = \tilde{\tau}. \tag{3}$$

Here,

$$\tilde{\tau} = \Gamma^T \tau = \Gamma^T \begin{bmatrix} \mathbf{0}_{5\times 1} \\ \tau_\delta \\ \tau_\rho \\ \mathbf{0}_{5\times 1} \end{bmatrix} \tag{4}$$

Here, $\tau$ denotes the set of motor torques acting on the system. Equation 2 and 3 together represent the complete dynamics for the system.

## 4 Results

In this section, we present results for control of the theoretical and experimental models. We will compare the two sets of results and show how rider input can affect the system greatly.

### 4.1 Simulation results

The ROBOTRIKKE was simulated by applying different controls on the steering angle $\delta$. A sinusoid was used to specify the desired trajectories for the control variable:

$$\delta_d = \delta_o + \delta_a \sin(\omega_\delta t + \phi_\delta), \tag{5}$$

Feedback linearization can be used to obtain direct control of the input variable. Thus, using an appropriate control law, we have $\ddot{\delta} = u_1$ where $u_1$ is the control input. In practice, the use of a servo motor on our robot allows us to directly specify the desired angles and thus justifies our assumption of direct control on the input variables.

The action of the actuator that moves the rider corresponds to the torque exerted at the hip by a human rider to swing his upper body from side to side. The input for the rider is also specified as a sinusoid.

$$\rho_d = \rho_o + \rho_a \sin(\omega_\rho t + \phi_\rho). \tag{6}$$

Figures 10 and 11 show the response of the system to 3 different inputs: (1) A zero rider input where the rider is controlled so that $\rho = 0$, (2) In-phase inputs specified as $\rho_a = \delta_a$ and $\phi_\rho = \phi_\delta = 0$ and (3) Out of phase inputs where $\rho_a = \delta_a$ and $\phi_\rho = \pi$ and $\phi_\delta = 0$.

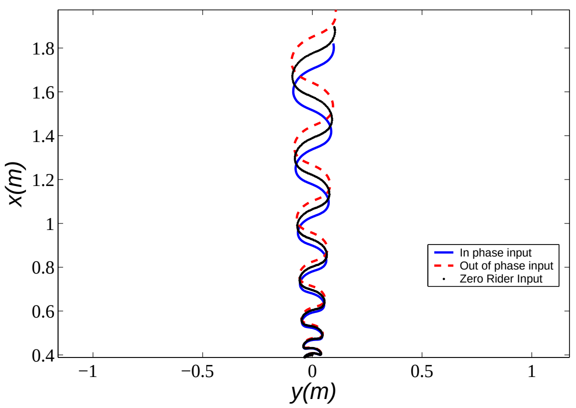



Figure 10. ROBOTRIKKE (Simulation): Trajectory of system for in-phase, out of phase and zero rider input.

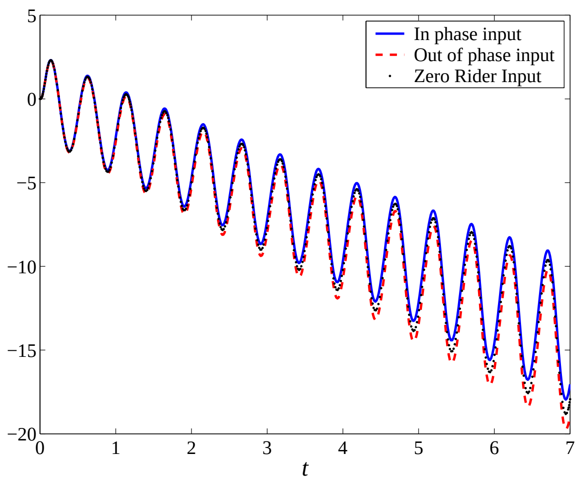



Figure 11. ROBOTRIKKE (Simulation): Angular velocity of rear wheel for in-phase, out of phase and zero rider input vs. time.

The simulations confirm that rider input has a definite effect on the motion of the system. The case of in-phase inputs corresponds to the rider leaning away from the direction in which the steering handle is turned. This kind of rider input slows down the system. The out of phase motion corresponds to the rider leaning into the direction the steering handle is turned which is seen to speed up the system. This kind of behavior is exploited by human riders of the TRIKKE system who *rock* from side to side to impart greater momentum to their vehicles.

## 4.2 Experimental Results

In this section, we present experimental results for our prototypes. A servo mounted on the rear platform of the prototypes actuated a four-bar linkage that moved a weight from side to side

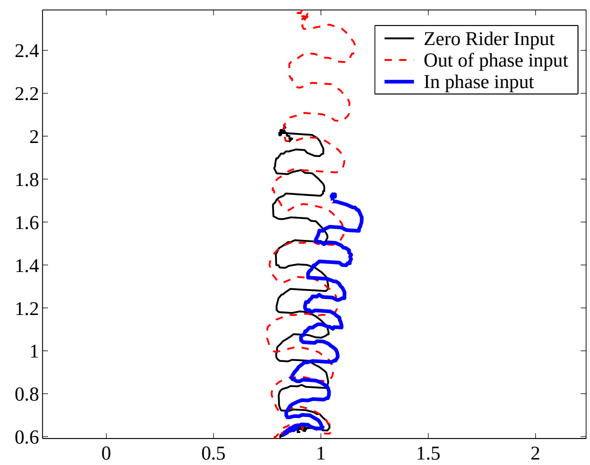



Figure 12. Experimental trajectories of the ROBOTRIKKE for in-phase, out of phase input and zero rider input.

(Figure 6). This mechanism replicated the effect of a rider swinging from side to side on the actual TRIKKE and on the model of the ROBOTRIKKE.

The prototypes were actuated with a similar set of inputs as used in the simulation. Figure 12 compares the experimental trajectories for the three different cases of inputs for the *non-sdm* version of the ROBOTRIKKE. In each case, the experiments were performed by actuating the robot with the desired set of inputs for a fixed number of gait cycles. The results show that phasing the inputs correctly can provide additional benefits in riding a vehicle like the TRIKKE. Again, *out of phase* inputs correspond to the rider leaning in the same direction as the direction in which the front steering handle is turned. As can be seen from both the theoretical and experimental results, this input results in a greater build-up of momentum and the ROBOTRIKKE travels further than in the *in-phase* and *zero* input cases (for the same amplitude and periods for all the inputs).

Figure 13 shows the experimental results for the SDM based prototype. This prototype had a narrower base and the effect of the swinging rider was more pronounced here. The data shown in the Figure is from 4 different experimental runs with the same set of inputs. The data clearly shows the benefit of leaning in the right direction as the steering handle is rotated. Out of phase inputs clearly show the greatest improvement in increasing the speed of the ROBOTRIKKE.

The models manufactured using both traditional and SDM techniques performed well in the experiments. The benefits in using SDM for making robotic prototypes is the reduction in use of threaded fasteners and the greater robustness of the prototype. The unique front axis steering joint was also easier to manufacture using SDM and demonstrated the benefits of combining materials of different stiffness.

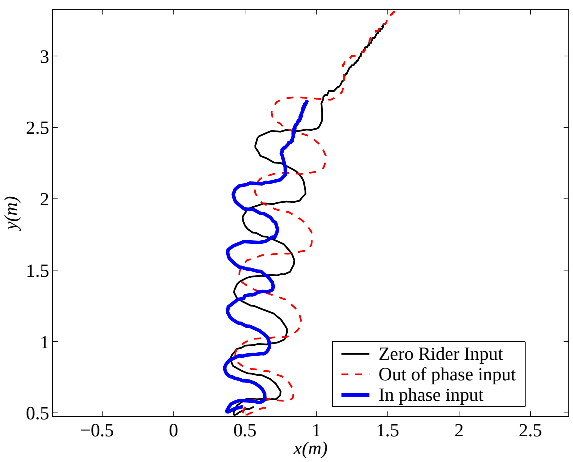



Figure 13. Experimental trajectories for the ROBOTRIKKE for in-phase, out of phase input and zero rider input.

## 5 Conclusion

In this paper, we have presented a basis for actuating a novel, two-input robotic system called the ROBOTRIKKE. The inputs are the steering input and the side-to-side swaying motion of a robotic rider. We have shown how a particular choice of phasing of the inputs to this system leads to different responses. The effect of rider control on systems like this (and bicycles) has not been widely studied and this work provides new insight and a basis for further work in this area. It is obvious that exploiting the dynamic behavior of the system leads to better performance. The resultant gaits for the system also closely resemble the motion of a human driven system of the same kind.

In our work, we have been studying the locomotion of novel locomotion systems and unconventional actuation schemes [8,9]. We have been able to show how the rider can exploit the dynamics of the system to their advantage. The general ideas presented on this system can also be applied to other applications where quick changes of direction are desired, *e.g.* legged robots running at higher speeds. We hope to further examine such applications in future work.

## 6 Acknowledgements

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| Parameter | Description | Value |
|---|---|---|
| $w$ | Wheel base | 0.4 m |
| $t$ | Trail | 0.04 m |
| $\alpha$ | Steering tilt | 72deg |
| ***Rear wheel(RW)*** | | |
| $R_{rw}$ | Radius | 0.03 m |
| $m_{rw}$ | Mass | 0.1 kg |
| $I_{rw}$ | Moment of inertia about $Y$ axis | $0.012\text{kgm}^2$ |
| ***Rear frame (RF)*** | | |
| $(x_{rf}, y_{rf}, z_{rf})$ | Position center of mass | $(0.12, 0, 0.08)$ m |
| $m_{rf}$ | Mass | 1.5 kg |
| $(I_{yy}, I_{zz})$ | Mass moment of inertia | $(0.12, 0.12)\text{kgm}^2$ |
| ***Front frame (FF)*** | | |
| $(x_{ff}, y_{ff}, z_{ff})$ | Position center of mass | $(0.28, 0, 0.07)$ m |
| $m_{ff}$ | Mass | 0.5 kg |
| $(I_{xx}, I_{yy}, I_{zz})$ | Moment of inertia | $(0.006, 0.006, 0.0012)\text{kgm}^2$ |
| ***Front wheel (FW)*** | | |
| $R_{fw}$ | Radius | 0.03 m |
| $m_{ff}$ | Mass | 0.1 kg |
| $(I_{xx}, I_{yy}, I_{zz})$ | Moments of inertia | $(0.006, 0.012, 0.006)\text{kgm}^2$ |
| ***Rider*** | | |
| $(x_{ri}, y_{ri}, z_{ri})$ | Position center of mass | $(0, 0, 0.25)$ m |
| $(x_{le}, y_{le}, z_{le})$ | Rider hinge position | $(0, 0, 0.0.08)$ m |
| $m_{ri}$ | Mass | 0.3 kg |
| $I_{ri}$ | Mass moments of inertia | $\begin{bmatrix} 0.20 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{kgm}^2$ |

Table 1. ROBOTRIKKE Model parameters.