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A Narrow-Track Tilting Tricycle with Variable Stability that the Rider can Control Manually

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ABSTRACT

Many health, environmental, and quality-of-life benefits to cycling have been identified, including exercise, zero-emissions, reduced pavement requirements compared to cars and busses, and nearly silent operation. [1] There has also been a huge recent world-wide investment in infrastructure, including kilometers of lanes and paths, parking, bike share, and shower facilities at workplaces. [2] A significant fraction of the population, however, is unable to join in this activity with traditional upright bicycles, including people with balance or joint limitations caused by injury, disease, or age. [3]

One solution to these ergonomic difficulties is the recumbent bicycle, but many riders find them difficult to balance and steer because of several factors, including centre of mass location and steering geometry. [4] Another solution, the recumbent tricycle, must have a wide axle track for lateral stability when turning, which requires more pavement and creates more aerodynamic drag than the bicycle equivalent. [4] Tilting tricycles can behave just like bicycles and so have the same handling issues or incorporate complicated and costly tilting actuation. [5][6]

We present a solution that aims to combine the best attributes of all these vehicles and eliminate the drawbacks: a tilting tricycle with variable stability that the rider can control manually. By varying the centre of mass trajectory while tilting, it balances like a bicycle when going fast and so has lateral stability provided by tilting like a bicycle, and it balances like a tricycle when stopped or going slow to eliminate excessive steering burden on the rider. [7] It also requires no more pavement than a bicycle and has little more aerodynamic drag than a recumbent bicycle because of its narrow track.

An additional beneficial side-effect of the variable tilting mechanism is that the seat can be higher when stable to facilitate getting in and out of it, and the seat can be lower when unstable to reduce frontal area and therefore aerodynamic drag.

We present the titling linkage that implements this functionality, a mathematical model and the stability eigenvalues it produces, and confirmation of the model with a ridable physical prototype.

Keywords: tilting tricycle, narrow track, variable stability.

1 INTRODUCTION

1.1. Why Tilting Tricycles

The quality-of-life and environmental benefits of cycling are now well known. It is a healthy, low-impact, and enjoyable form of exercise for all ages with zero emissions, small pavement requirements, and near silent operation. [1] Investments in cycling are being made worldwide to connect the infrastructure of countless cities and their citizens through kilometers of new bike lanes and paths, parking, and bikeshares. [2]

A significant fraction of the population, however, is unable to enjoy cycling with traditional upright bicycles due to balance, joint, or other physical limitations. [3] Those able to ride are prone to experience neck hyper-extension, back and muscle spasms, saddle sores, and cervical spine strains [8]. The problematic ergonomics of upright bicycles is coupled with less-than-optimal aerodynamics. [9]. Alternatives to traditional upright bicycles continue to be investigated to address these limitations.

Recumbent bicycles offer improved ergonomics, but many riders find them difficult to balance and steer. Recumbent bikes typically have a broad and comfortable seat and rider position, but the seat is often low, which can lead to awkward and difficult mounting and dismounting. [4]

Rigid recumbent tricycles are more stable and easier to learn to ride than recumbent bicycles. Unfortunately, they can become unstable when cornering at higher speeds, [4] and the vehicle and rider are subject to side loads in a turn or on a slide slope and roll accelerations from uneven pavement. [4] Although easier to leisurely ride than recumbent bicycles, recumbent tricycles must be low, wide, and/or slow to avoid rolling over in a turn, and the necessary low seating position provides poor visibility to the rider of surrounding traffic and to surrounding traffic of the rider. [4]

Figure 1. An upright bicycle, a recumbent bicycle, and a rigid recumbent tricycle, from left to right. (all images from Wikimedia Commons)

We present a tilting recumbent tricycle with variable stability that aims to combine the best attributes of bicycles and tricycles while simultaneously minimizing their drawbacks. It can lean like a bicycle when the rider wants and stay upright like a tricycle when the rider needs. It combines the ergonomic and aerodynamic benefits of recumbent bicycles with the stability benefits of recumbent tricycles while it reduces the handling difficulties of recumbent bicycles and minimizes the pavement requirements, side loads, and undesired roll of recumbent tricycles.

1.2. Tilting Tricycle Linkages

There are at least three known mechanisms that have been implemented to provide tilting of side-by-side wheels: cranks, a parallelogram, and a bell crank with swing arms.

The crank implementation consists of two wheels mounted on crank, where the pedals would normally attach. Crank tilting linkages were successfully implemented in Vi Vuong’s tilting tricycle and Nurse’s Leaning Tricycles (NLT’s). [Figure 2] A drawback is that the pair of wheels are no longer side-by-side, unless they are at the maximum possible tilt angle, and so must develop slip angles or actually slide when in a turn, depending on the crank length, tilt angle, and turn radius.

Figure 2. Vi Vuong's tilting tricycle and Nurse Leaning Tricycles (NLT's).

The parallelogram implementation keeps the wheels parallel to one another and side-by-side when tilted, as shown in Figure 3. Examples include the commercially-available Tripendo and Paul Sims' openly-documented parallelogram tilting tricycle. An advantage to this mechanism is that it can support different camber angles for the two wheels so that, for example, the inner wheel in a turn has more camber than the outer wheel.

Figure 3. Tripendo and Paul Sims' openly documented parallelogram tilting tricycle.

The bell crank and swing arms implementation consists of a wheel mounted to each swing arm, and the swing arms are connected by tie rods to the bell crank to enforce the constraint that one swings up as the other swings down during tilting, as shown in Figure 4. A drawback is that the projections of the wheels on the ground plane move apart while tilting and so the tires must develop slip angles or actually slide when tilting, depending on the ratio of the forward speed and tilt rate.

Figure 4. Bell crank, tie rod, and swing arm mechanism.

1.3. Tilt Control

There have been many implementations of titling tricycles over the years, some which have achieved commercial success, and most depend upon explicitly controlling the tilting mechanism, either by the rider or by some automation. Because of weight and cost limitations on human-powered vehicles, tilt control has been limited to the rider on these vehicles, if available at all, with a control lever as in the case of the Tripendo, or simply an on-off "lockout" often implemented with a disc brake or the equivalent somewhere in the tilting linkage.

The bell crank and swing arm linkage, on the other hand, offers the opportunity to control the trajectory of the part of the vehicle to which it connects while tilting. On a delta-configuration tricycle, with one wheel forward and two wheels aft, this is approximately the seat. If the linkage is "square", the bell crank is the same width as the swing arms and has no offset, and the tie rods are parallel, then the seat follows the same trajectory as it would on the equivalent bicycle. If the linkage is not "square", the bell crank is narrower than the swing arms and/or it has an offset, then the seat may fall less than it would on the equivalent bicycle. It is possible to vary this geometry enough to eliminate "seat fall" entirely during tilting, giving the vehicle neutral static stability when stationary, [10] or even create negative seat fall, giving the vehicle positive static stability when stationary.

Further, the bell crank and swing arm linkage can be arranged so that when unstable and not tilted the seat is lower than when stable and not tilted, and this provides an opportunity to optimize further the behavior of the tilting tricycle. A low seat height minimizes aerodynamic drag when balancing like a bicycle, and a high seat height facilitates getting into and out of the seat stable like a tricycle.

2 LITERATURE REVIEW

2.1. Recumbent Bicycles

Schwab, Kooijman and Nieuwendijk [11] adapt the Whipple bicycle model [12] to recumbents and use it to replicate the handling characteristics of one design in a distinct design with two separate configurations. Their success validates the model and supports their assumption that the theoretical, uncontrolled vehicle dynamics correspond to experimental characteristics. Further work on recumbent modeling was performed by Epema et. al., [13] who use modeling software developed in MATLAB® and ADAMS® to design a high-speed human powered vehicle with favorable handling.

2.2. Rigid Tricycles

Dynamic stability of rigid tricycles is described Ekuase et. al., [14] in consideration of the rollover threshold for cargo bearing vehicles on public highways.

2.3. Tilting Tricycles, Active Control, Automotive

Some research has also previously been done related to tilting tricycles. Vieira et. al. [15] recapped the design history of automotive tilting tricycles and developed a multibody model and the corresponding equations of motion. Their proposed vehicle uses a tadpole configuration, with two wheels forward and one wheel aft, and an active control system to actuate the tilting mechanism.

Edelmann and Plöchl [16] generated the equations of motion for a delta-configuration tilting tricycle. Assuming that a light, three-wheeled vehicle will have greater appeal if it handles like an automobile and, based on stability eigenvalues generated from their model, they developed an electronic, assisted tilting system. A prototype of the "motorcycle-like vehicle" [5] was constructed and successfully driven with the control system. In order to make the performance more intuitive, the researchers have proposed continued study on the driver and control system interaction.

The two designs described above utilize parallelogram linkages to enable the tilting motion. Kim et. al. [17] describe a tilting tricycle which uses independent suspension and active control to camber the two front wheels. Simulations of the proposed vehicle compared with those of a similar, non-tilting version demonstrate significant reduction in turn radius at various speeds and steering angles.

Zandieh [18] also modeled a tadpole-configuration tricycle with independently controlled front wheels. She analyzed handling and stability in several cases in the interest of improved performance in extreme maneuvers.

2.4 Tilting Tricycle, Passive Control, Human Powered

While the majority of tilting tricycle research has focused on motor-driven vehicles, several human-powered vehicles have been developed in various configurations. A notable example is Wim Schermer's VeloTilt, [19] which has tilting rear wheels attached to a frame by swing arms and a bell crank. Tilting is not controlled directly, as with a bicycle, and a separate mechanism is available to create static stability. A cable-actuated clamp allows the rider to lock the bell crank in place, fixing the wheels in their orientation.

3 IMPLEMENTATION

3.1 Kinematics

Previous builders of tilting tricycles with swing arm and bell crank linkages have found that static roll stability varies with linkage geometry. [10] The have found that three distinct behaviors are possible: statically unstable, neutrally stable, and statically stable. In the unstable configuration, the seat height falls as the vehicle leans, thus making it behave like a bicycle and able to lean into turns. In the stable configuration, the seat height increases as the vehicle leans, thus making behave like a rigid tricycle and be suitable for low speeds or when stopped. Between these two extremes is a configuration that exhibits the neutral stability of a "bricycle", a self-balancing tilting tricycle that can be balanced or steered but not both.[7]

We developed a 3D kinematic model in MATLAB® to assess the functionality of the tilting mechanism as geometry varies. For any set of dimensions, it varies the bell crank rotation in a programmatic loop, and at each orientation uses MATLAB's root finding function, fzero() to find the swing arm orientation that matches the specified tie rod length. Finally, with each swing arm orientation, it can calculate the seat height, tilt angle, and pitch angle from the rear wheel positions.

The results from the simulation show that the mechanism behaves as desired in each configuration, with the seat height decreasing with lean like a bicycle in the unstable configuration, and the seat height increasing with lean in the stable configuration, as shown in Figures 5 and 6. The increase in seat height generates a tendency for the vehicle to center itself, exhibiting static self-stability, similar to a rigid tricycle.

Of the many possible configurations and orientations of bell crank, tie rods, and swing arms, we chose one that always keeps the tie rods in tension, to avoid issues with buckling, and the bell crank also in tension, to avoid instabilities in which it would tend to flip around. We also chose to orient the tie rods and bell crank so that they project straight back between the two wheels for easy access. This required us to add dog legs to the swing arms for the forward tie rod attachment points.

We use bell crank “width” to mean the distance between the two tie rod attachment points and bell crank “offset” to mean the normal distance between the bell crank pivot point and a line connecting the two tie rode attachment points.

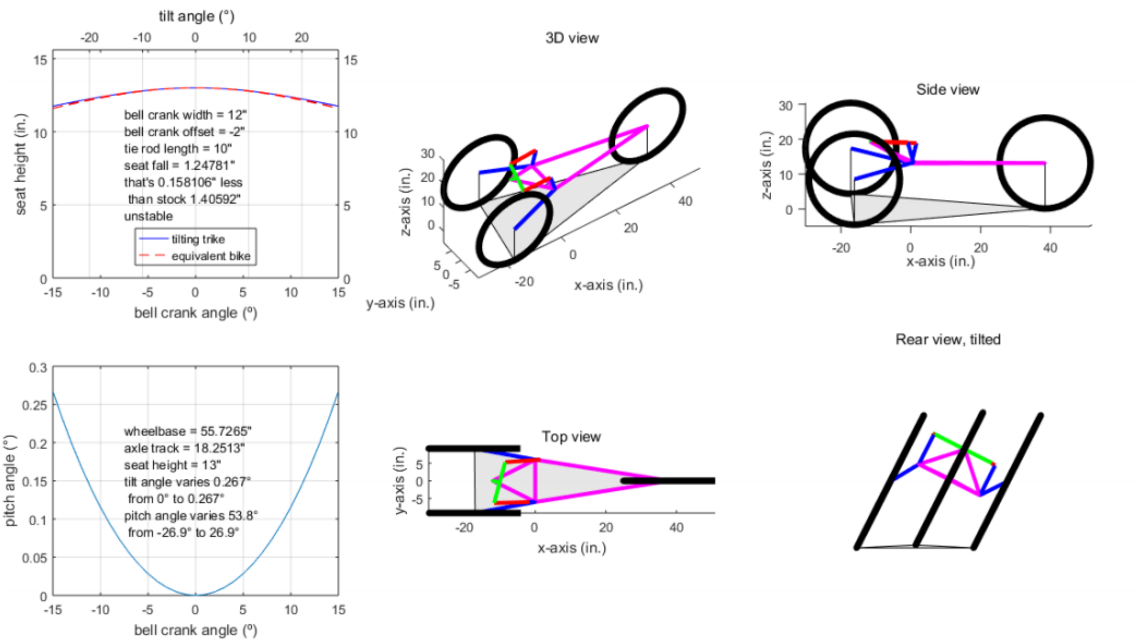

Figure 5. Kinematic analysis of tilting mechanism when statically unstable: seat falls with tilt like a bicycle.

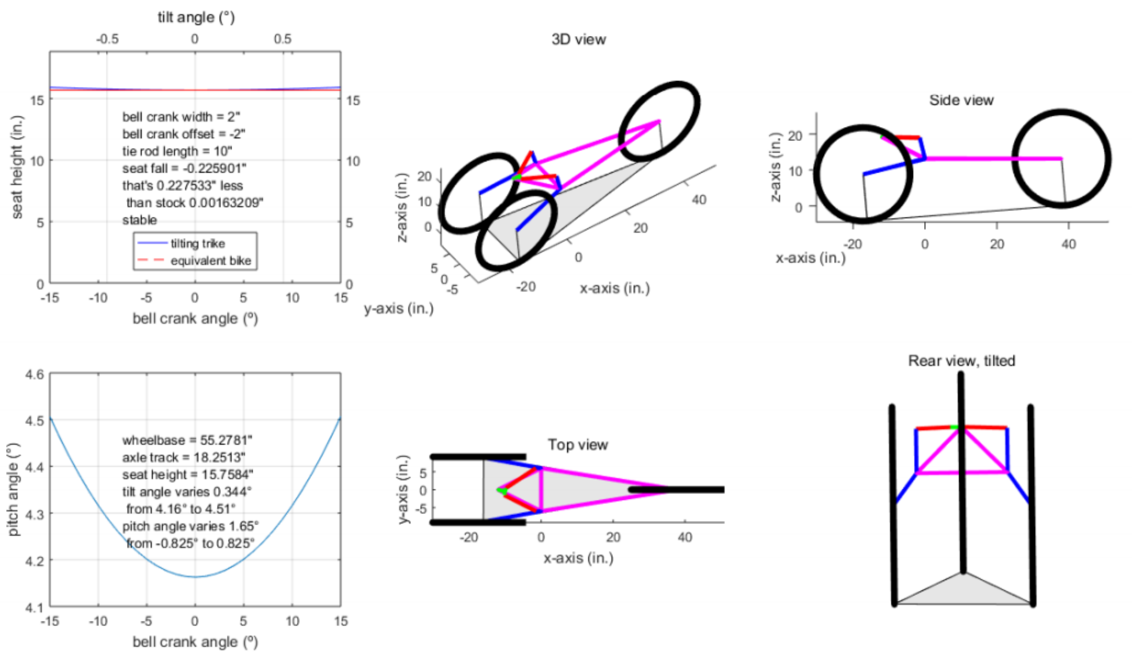

Figure 6. Kinematic analysis of tilting mechanism when statically stable: seat rises with tilt.

The model also shows that the relationship between seat height and stability may be manipulated for other favorable behaviors. Straight-up seat height may be changed at the cost of raising and lowering the rider’s mass during actuation. No change in seat height may be desirable to reduce forces otherwise necessary for actuation. The tie rod end trajectory is a circular arc for no change in straight-up seat height. The change in straight-up seat height varied by one hundredth of a percent from stable to unstable when we simulated a circular arc in MATLAB®. The most stable configuration is when the tie rod attachment point on the bell crank is in a straight line between the bell crank pivot point and the tie rod attachment points on the swing arms.

Figure 7 relates vehicle motion and the two main bell crank dimensions: width and offset. A large lean angle is very desirable when unstable to facilitate cornering and to avoid rolling. A lean angle is not necessary when stable.

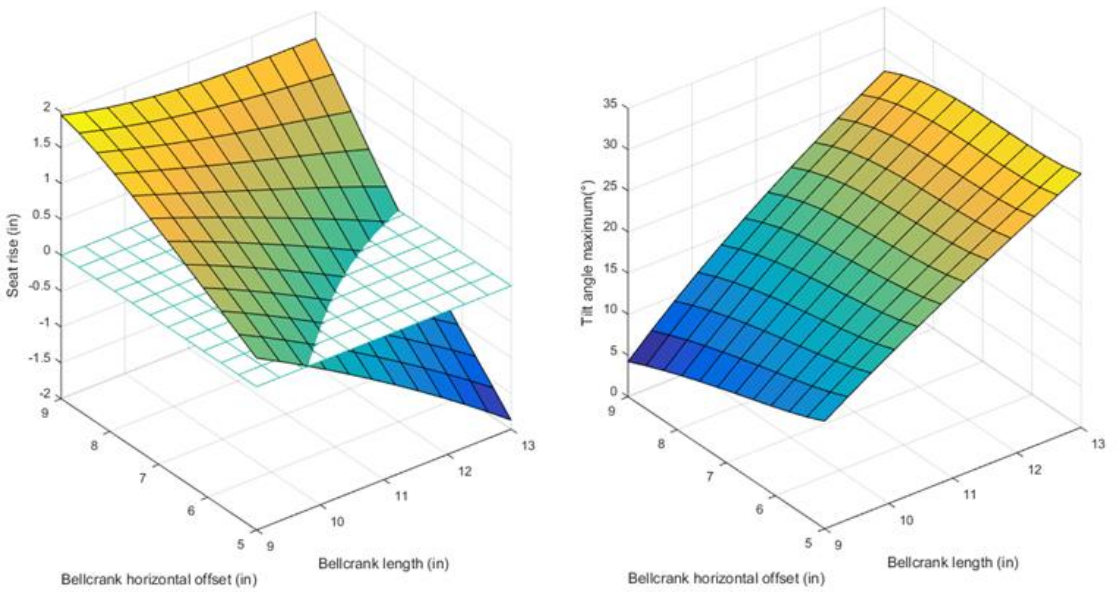

Figure 7. Survey of linkage parameter space.

Figure 8 examines the necessary tilt angle to prevent vehicle roll-over while turning. The program accounts for center of mass height (h), axle track width (w), and an assigned coefficient of friction of one between the tires and pavement. The appropriate bell crank dimensions for the vehicle were interpreted from this surface to achieve the desired narrow axle track width.

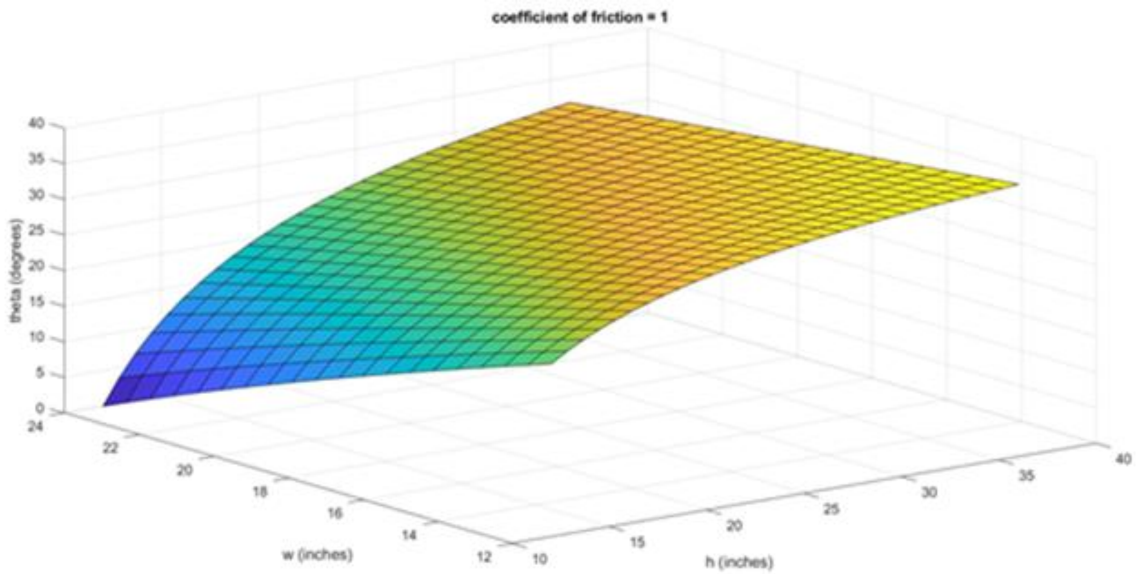

Figure 8. The minimum lean angle that needs to be produced by the tilting mechanism based on different bike geometries.

Figure 9 illustrates how the expected change in pitch will change the vehicle's front wheel trail. A change in pitch is a result of a change in seat height. The model is used to select a wheelbase, steering axis angle, and fork offset to correspond with the front wheel diameter. The careful refinement of these variables yields pleasing handling characteristics.

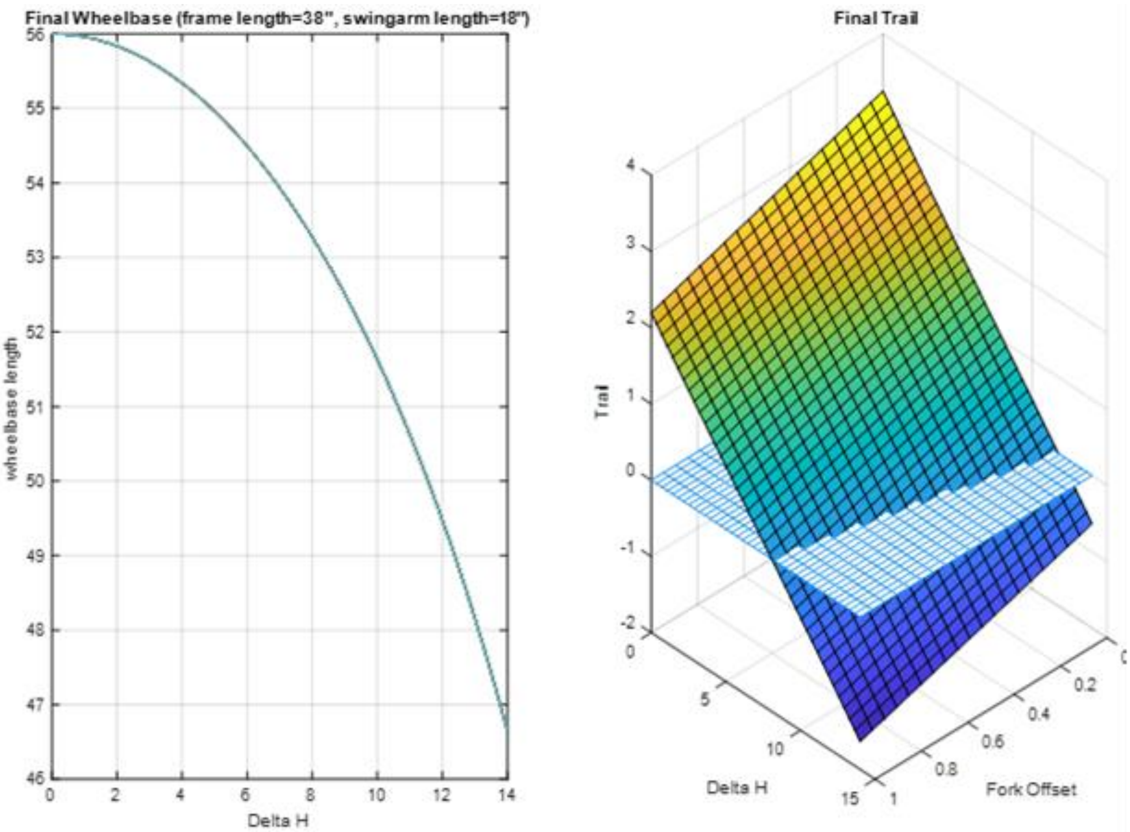

Figure 9. Investigation of how change in pitch caused by raising seat effect trail.

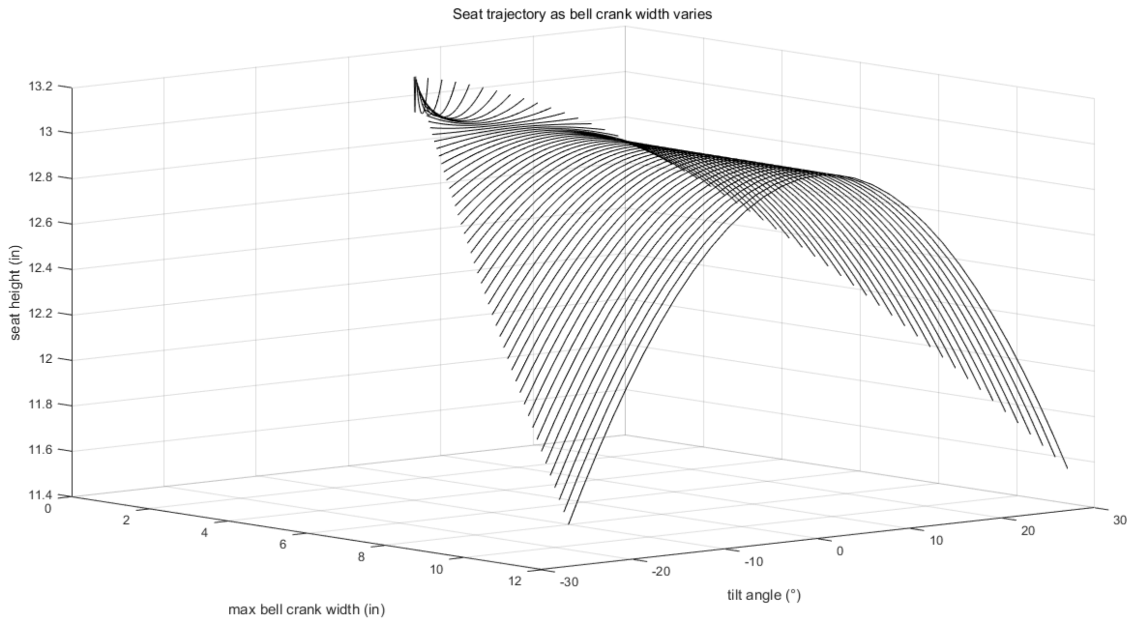

Figure 10. Showing how the seat trajectory varies with the bell crank geometry.

Figure 10 shows how the seat trajectory varies with the bell crank geometry, which is implemented by moving the tie rod connection point locations on the bell crank. When they are all the way out at 12", and the mechanism is "square", the seat falls exactly the same as it would on the equivalent bicycle. When they are all the way in at 1.71", so that they fall on the straight line between the swing arms and the bell crank pivot, the seat rises, and the tricycle is statically stable. When they are 4" apart, the seat neither rises nor falls as the tricycle tilts, and it shows neutral stability, like the Bricycle. When leaned and released, it neither leans further nor centers itself. Also, in order for the straight-up, no-tilt seat height to remain at 13" for all bell crank widths, the bell crank offset must vary from 0" to 1.43" as the tie rod ends follow circular arcs. Finally, the maximum tilt angle also decreases with bell crank width, as indicated by the shorter curves. This suggests the added benefit of switching to stable mode also bringing the tricycle back to vertical.

3.2 Dynamics

To understand better how the vehicle behaves as the tilting linkage geometry varies, we developed a numeric dynamic model also in MATLAB®, that can produce stability eigenvalues and generate animations.

3.2.1 Method

From the many possible ways to model such a vehicle, we selected a method presented by Schwab, [20] a fully-nonlinear, numerical model of the idealized bicycle similar to the one presented by Meijaard, et al., [21] benchmarked by Dressel with a suggestion by Ruina, [22] and extend it from 4 bodies to 10: 1 rear frame, 1 front fork, 3 wheels, 2 swing arms, 2 tie rods, and 1 bell crank.

In the method Schwab describes, the Newton-Euler equations for each rigid body are combined with constraint equations into a “system of coupled differential and algebraic equations” (DAEs). [23] It uses “the coordinate projection method to minimize constraint errors” after each time step in the numerical integration, which is the 4th-order Runge-Kutta (RK4).

The motion of the swing arms causes the contact patches of the two rear wheels to move apart as the vehicle tilts, so they cannot simply be implemented with non-holonomic constraints as the front wheel, and the two wheels of a bicycle can. If the constraint on lateral velocity of just one rear wheel is removed, this eliminates the over-constrained condition, but introduces an asymmetry in the resulting motion. Instead, we found that alternating which rear wheel has the lateral velocity constraint with each time step is a suitable compromise.

The resulting numerical model is linearized by perturbing each state variable to calculate partial derivatives, assembling them into a matrix, and using MATLAB’s eig() function to calculate the eigenvalues of the resulting matrix. Since there are 10 x 6 = 60 position and orientation variables and 60 linear and angular rates, the 120 x 120 matrix yields 120 eigenvalues, all but 4 of which are at or near zero. These remaining 4 represent the 4 modes in which the idealized tricycle may move: lean and steer and their rates.

3.2.2 Stability Eigenvalues

As anticipated, the stability eigenvalues for the uncontrolled tricycle resemble those of a bicycle, with the same four modes, when the linkage is in fully-unstable mode, and the seat follows the same trajectory of the equivalent bicycle.

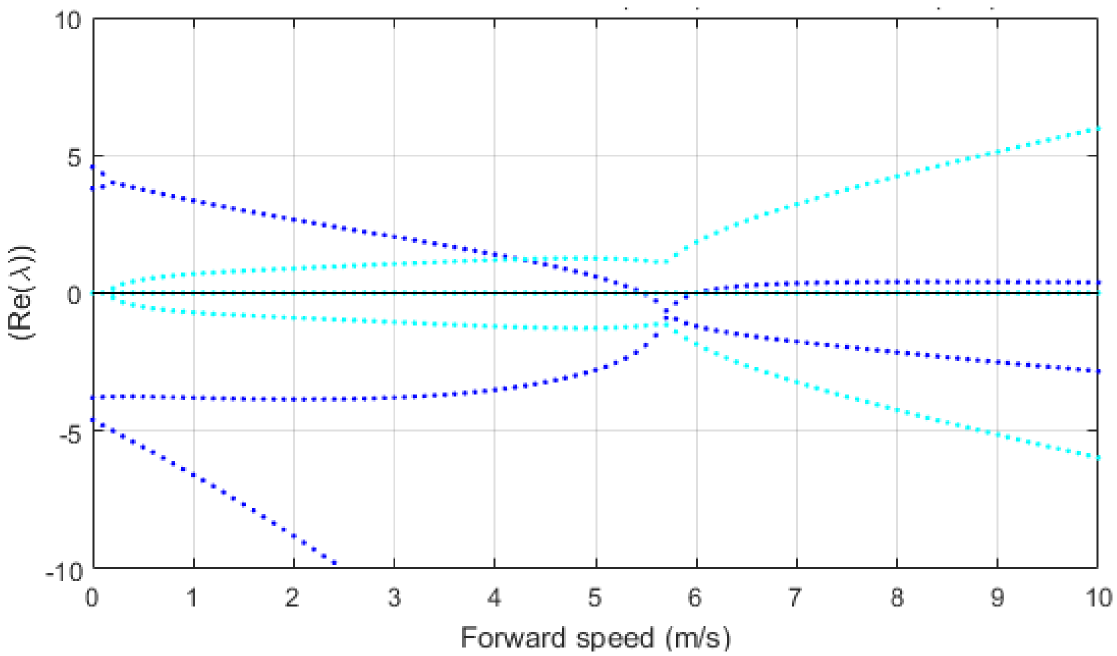

Figure 11. Stability eigenvalues from non-linear numerical simulation with bell crank width = 45.7 cm (18 in.) and offset = 0 cm (0 in.)

When the linkage is in fully-stable mode, and the seat actually rises as the vehicle tilts, there are still 4 modes present, some stable and some unstable, but it is not clear exactly what modes they represent.

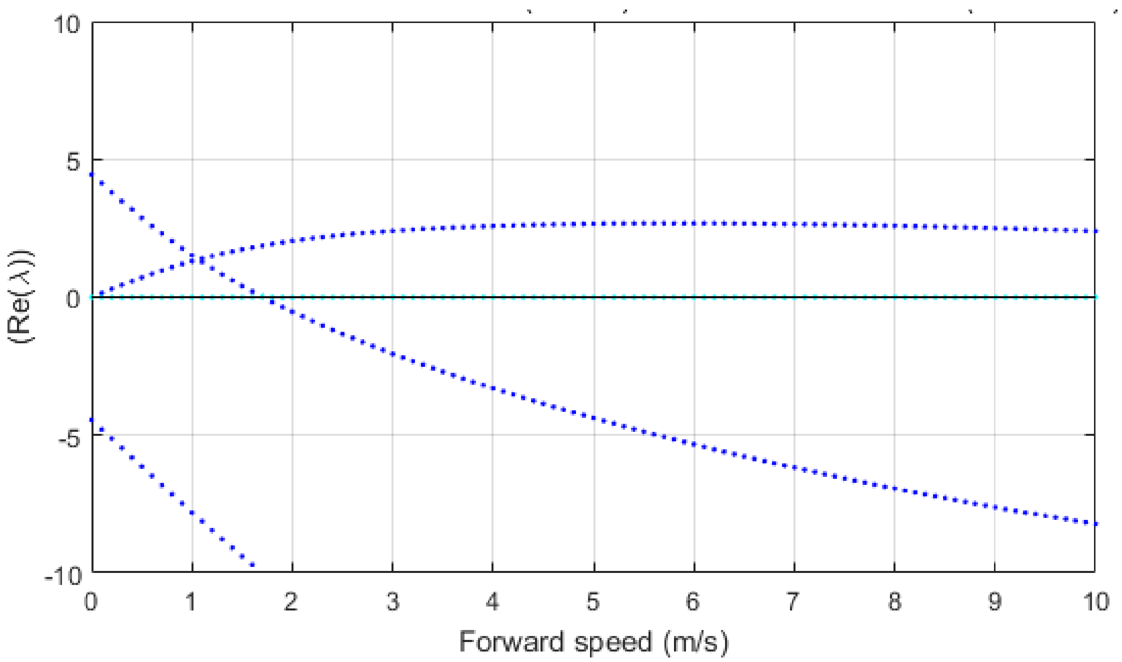

Figure 12. Stability eigenvalues from non-linear numerical simulation with bell crank width = 11.8 cm (4.64 in.) and offset = 6.5 cm (2.56 in.)

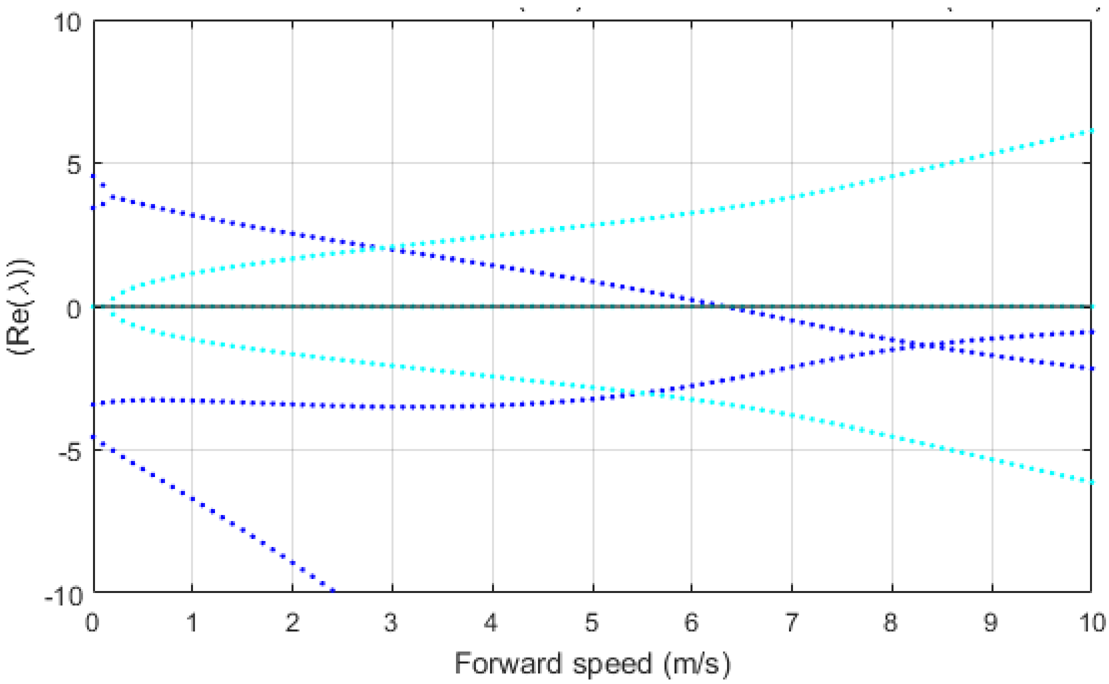

Figure 11. Stability eigenvalues from non-linear numerical simulation with bell crank width = 20.3 cm (8 in.) and offset = 3.4 cm (1.34 in.)

In between these two extremes, there is a smooth and continuous transition of the eigenvalues, indicating that the rider should not experience dramatic changes in behavior as the linkage geometry changes. This is confirmed by rider experience.

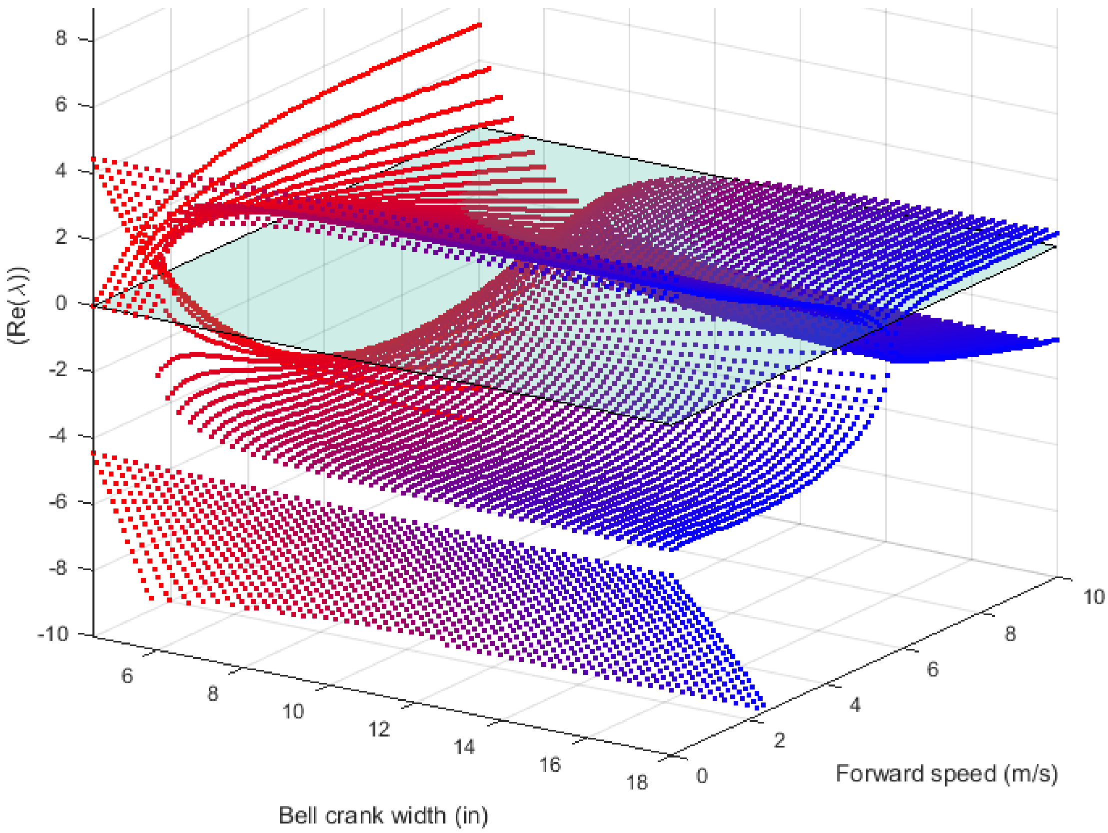

Figure 14. Eigenvalues from non-linear numerical simulation a bell crank width varies from 45.7 cm (18 in.) to 11.8 cm (4.5 in.) and offset varies from 0 cm (0 in.) to 6.5 cm (2.62 in.)

3.2.3 Compared to JBike6

The stability eigenvalues compare well with those generated by Papadopoulos's JBike6 for a bicycle of similar geometry and mass distribution.

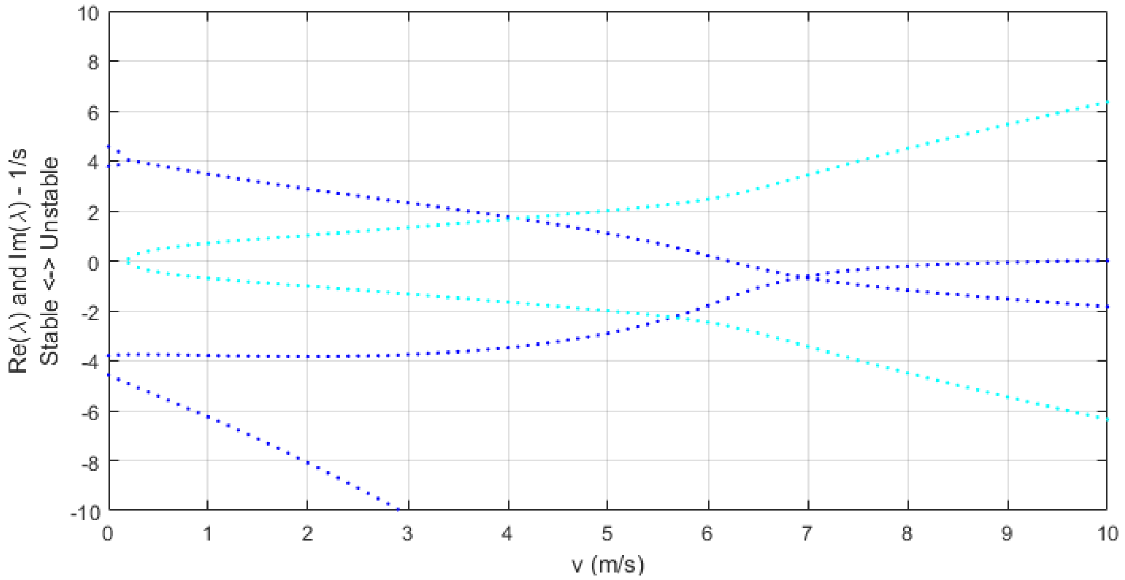

Figure 15. Stability eigenvalues generated by JBike6 for a bicycle with equivalent geometry and mass distribution.

3.2.4 Compared to SPACAR

The stability eigenvalues compare well with those generated by Schwab's SPACAR for a bicycle of similar geometry and mass distribution.

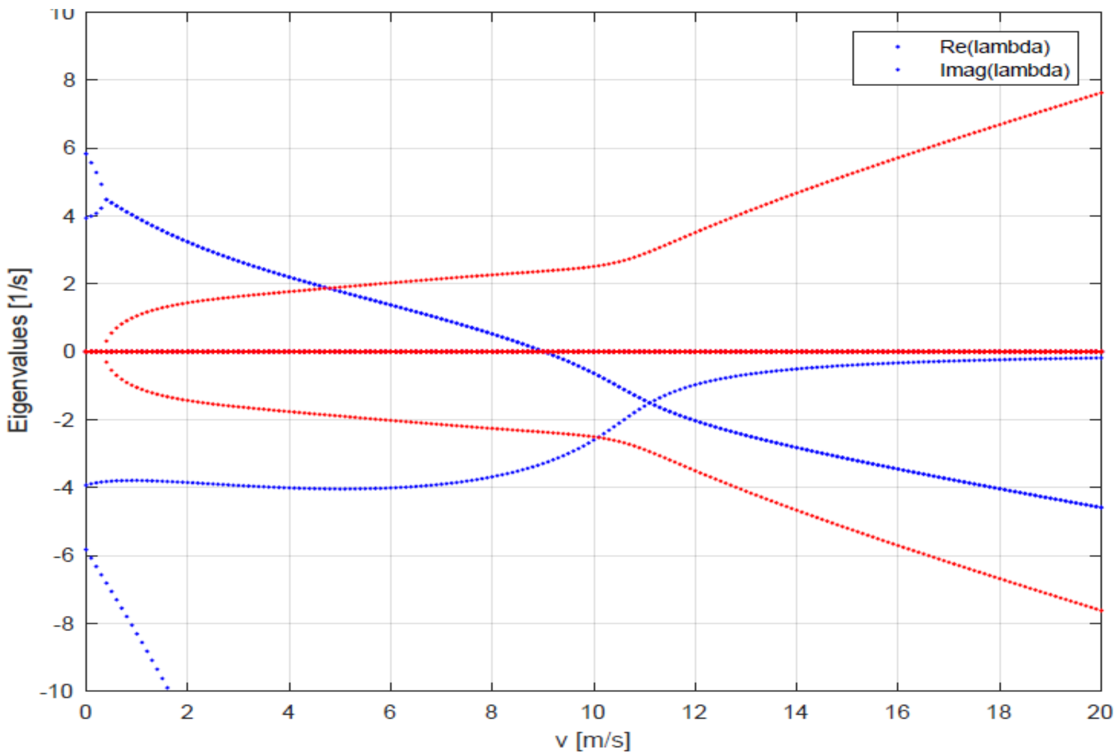

Figure 16. Eigenvalues generated by SPACAR for a tilting tricycle with the same geometry and mass distribution (generously calculated and contributed by Schwab).

3.2.5 Animation

It can be difficult to understand the complete motion of a multi-body system merely be examining plots of various positions and velocities with respect to time, and an animation can be a useful augmentation.

Following the example of Schwab again, we generate VRML (virtual reality markup language) code from the calculated positions and rotations of all the bodies, which can be animated with a VRML browser plug-in.

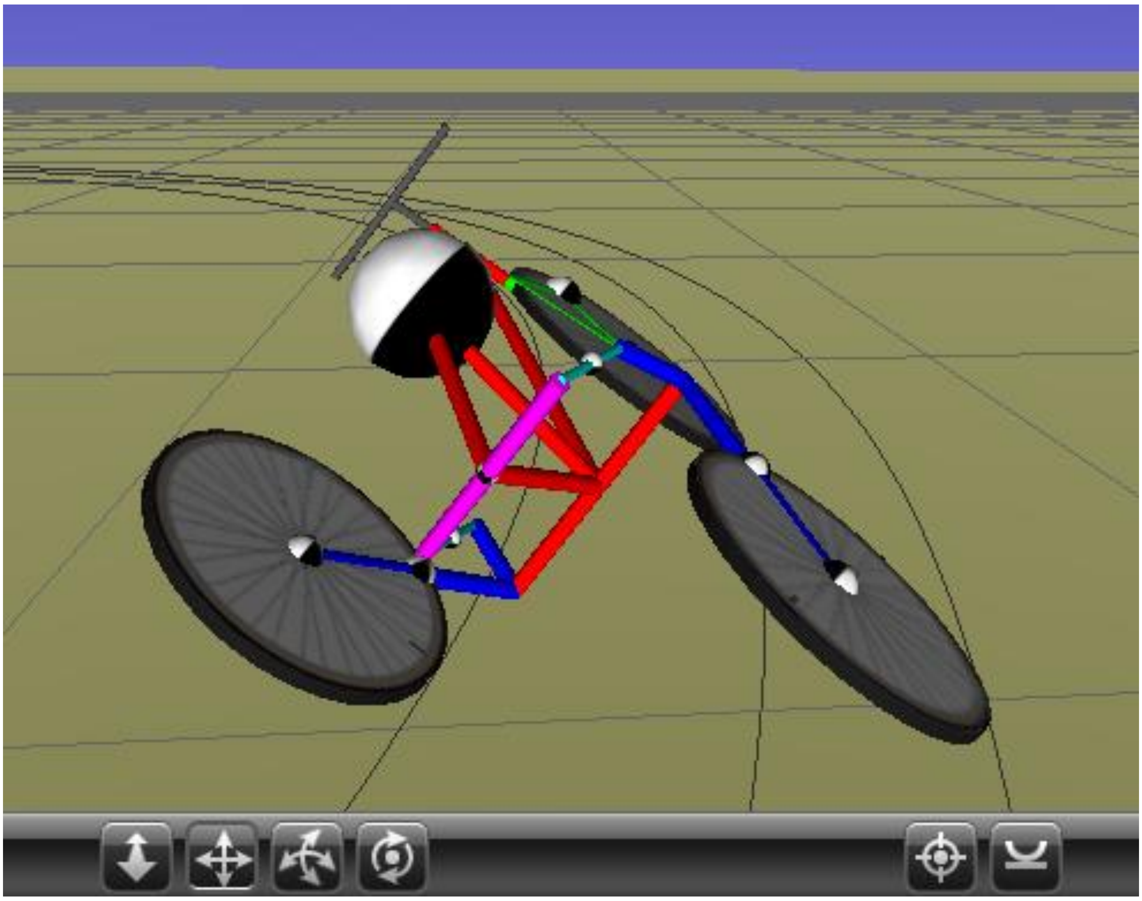

Figure 17. Still image captured from VRML animation rendered by the Cortona3D plug-in running on the Microsoft Internet Explorer 11 browser. The rear frame is red, the bell crank is magenta, and the swing arms are blue

3.3 Design, Construction, and Rider Perceptionsx

3.3.1 Design

We chose the delta tricycle configuration, instead of tadpole, in conjunction with front-wheel steering to eliminate the need to implement steering on the pair of side-by-side wheels and avoid all the additional complications of rear-wheel steering.

We used a "moving-bottom-bracket" (MBB) front end, shown in Figure 20, which was generously donated by Cruzbike. The MBB arrangement enables a simple and robust drivetrain to the front wheel, which eliminates the complication of driving one or both tilting rear wheels. This design also allows leg-length adjustment for different riders without moving the rider center of mass, but there is a learning curve associated with the steering torque generated under high-powered pedaling, and keeping feet on the pedals limits the possible steering angle to about 12°.

We performed solid modeling and finite element analysis with the Creo® software package by PTC, as shown in Figures 18 and 19.

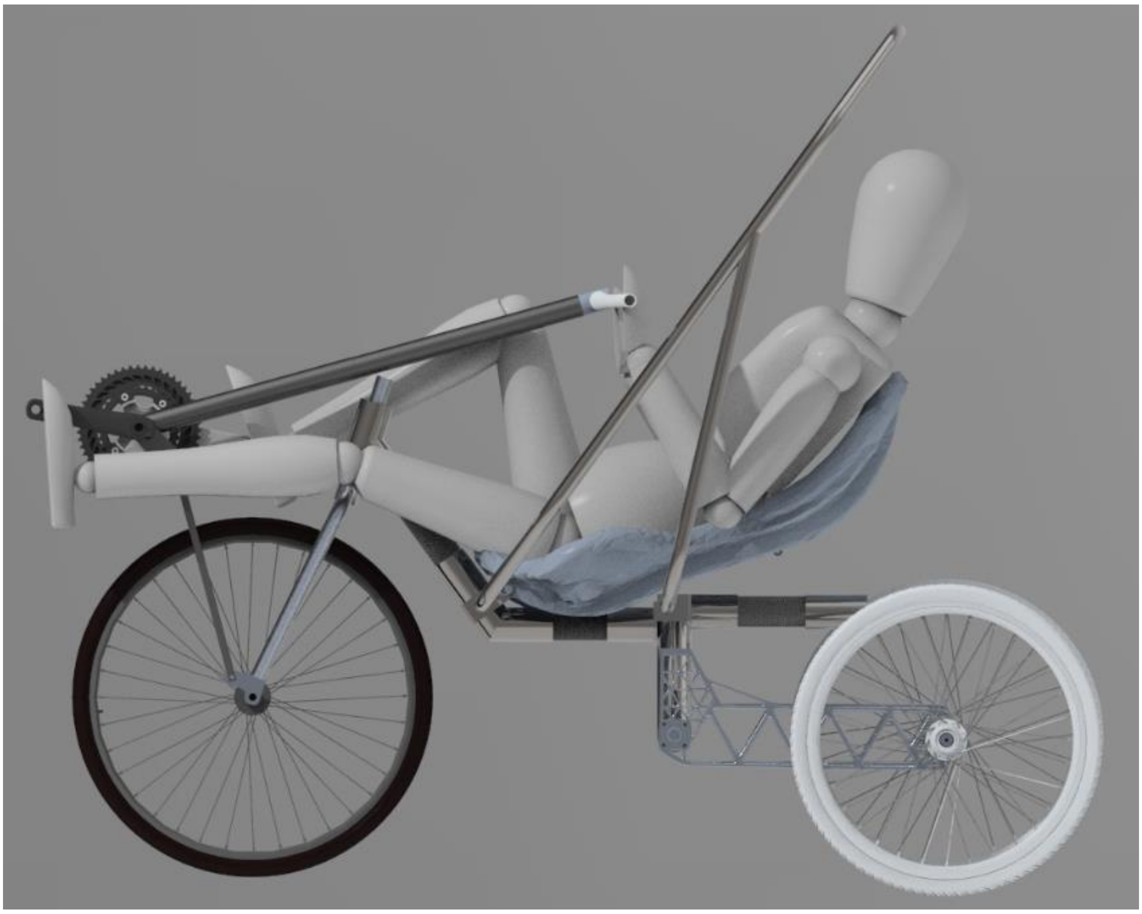

Figure 18. Solid model of complete tricycle with rider in Creo®. The roll cage, which was required to compete in the ASME HPVC, can also be seen.

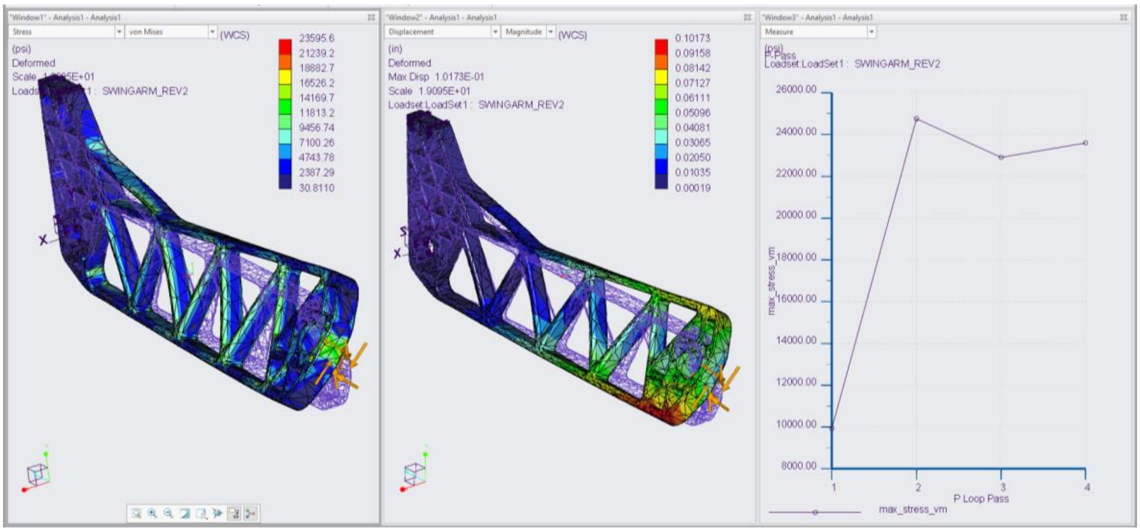

Figure 19. Finite element analysis of a swing arm in Creo®.

We chose an axle track, the distance between the two rear wheels, of about 48 cm (18 in.), which is narrow compared with most rigid tricycles. It is wide enough to provide static stability when stationary and narrow enough to easily ride in a bike lane, a slalom course, a hairpin turn, or other limited areas. It also tucks the wheels behind the seat in an attempt to minimize aerodynamic drag.

We based other frame geometry loosely on the Cruzbike Vendetta V20, a commercially successful racing-oriented recumbent bicycle. Because a tilting tricycle is free from the constraints on center of mass location faced by rigid tricycles, we also made sure that the line connecting the center of mass and the contact patch is less than 45 degrees above the horizontal to minimize the chances that the tricycle would pitch forward over the front wheel during hard braking.

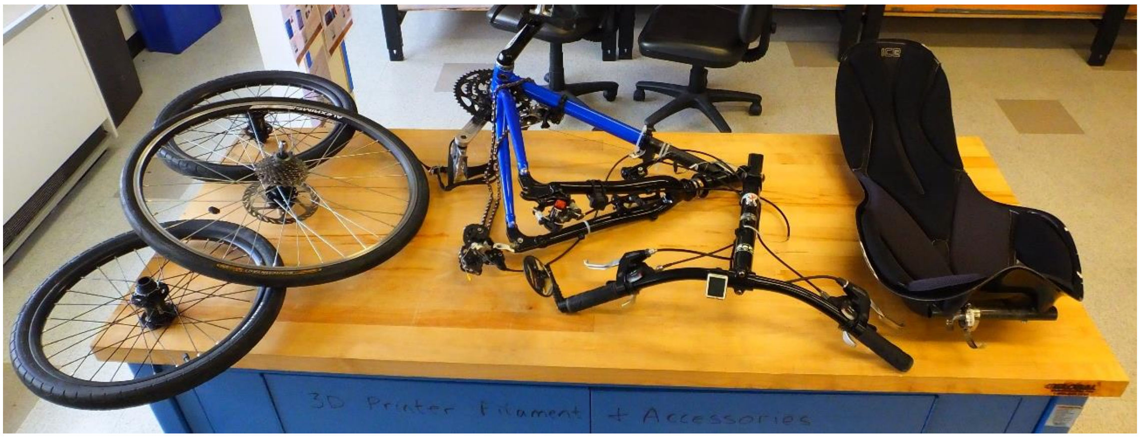

Figure 20. Cruzbike front frame, along with wheels, seat, stem, and handlebars.

We chose the front wheel diameter, ISO 559 mm, for compatibility with the donated Cruzbike front fork and drivetrain, and the rear wheel diameter, ISO 406 mm, as a reasonable compromise between rolling resistance, which tends to decrease with wheel diameter, and aerodynamic drag, which tends to increase with wheel diameter, all else remaining constant.

The seat is at an aggressively-recumbent angle of 25° above the horizontal partially to enable use of an existing seat from a previous competition vehicle and in an attempt to minimize aerodynamic drag. We borrowed the stem and handlebars from a Burley Canto recumbent bicycle.

We designed the frame with the shortest practical wheelbase 114.3 cm (45 in.), under the assumption that a shorter wheelbase would contribute to more agile handling.

Table 1. Tricycle dimensions.

Wheelbase	114.3 cm	45 in.
Axle track	48 cm	18 in.
Head angle	72° (from horizontal)	
Trail	4.4 cm	1.73 in.
Maximum steering angle	90° w/o rider, 12° w/ rider	
Minimum turning radius	5.65 m (when untilted)	18.55 ft
Bell crank width	30.5 to 4.3 cm	12 to 1.71 in.
Bell crank offset	0 to 3.6 cm	0 to 1.43 in.
Tie rod lengths	25.4 cm	10 in.
Swing arm length and height	45.7cm long, 15.2 cm tall	18 in. long, 6 in. tall
Maximum tilt angle	45° (from vertical)	
Total mass/weight	25 kg	55 lb

3.3.2 Construction

We constructed the rear frame by the "glued-lug" method, with the help of Trek Bicycle Corporation, where carbon fiber tubes are epoxied into steel lugs, as shown in Figure 21. The carbon fiber tubes offer a high strength to weight ratio for large parts of the frame, while steel for the lugs is easy to machine and fabricate and readily available. Microbeads are mixed into the epoxy to ensure an even bond is created. This method allows the use of lightweight carbon fiber without the need for an autoclave or vacuum, making it suitable for our prototype. The complete tricycle is heavy—about 25 kg (55 lb)—but strong, stiff and dimensionally accurate enough that the same construction technique could be used for production, although ideally with lighter lugs.

Tilting is implemented with a bell crank and swing arms as discussed above and shown in Figures 21 - 24. Linkage components do not remain in a single plane as the tilting mechanism actuates, and so the bell crank pivot and all tie rod ends are implemented as spherical joints, or the equivalent. The linkage is very sensitive to dimensional accuracy but is demonstrably functional.

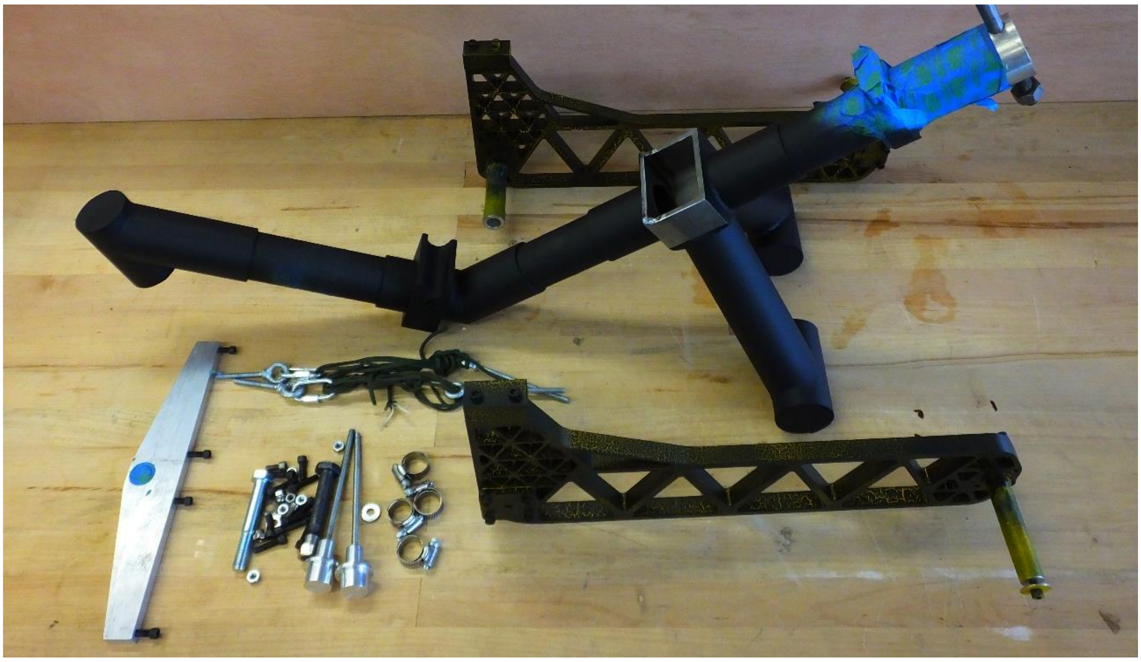

Figure 21. Rear frame, along with swing arms, initial bell crank, and other hardware.

The two swing arms, shown in Figures 21 – 24, were machined by water jet from solid billets of aluminum. In early test rides the swing arms developed a self-excited, side-to-side flutter at around 29 km/h (18 mph), which we easily damped by adding a small steel lanyard between the wheel axle and the swing arm axle, as shown in Figure 22.

Figure 22. Damping lanyard (thin, silver-looking wire) from swing arm end to pivot axle.

Since the tie rods are always in tension, by design, the swing arms and bell crank are linked using paracord, a lightweight, nylon, kernmantle rope, as shown in Figures 23 and 24, because it is more easily available and adjustable than a rigid tie rod. It has the incidental benefit of introducing some shock absorption but is problematic for establishing and maintaining dimensional accuracy.

3.3.3 Rider Perceptions

We did not have enough time to complete the rider-adjustable bell crank before the American Society of Mechanical Engineers Human-Powered Vehicle Challenge (ASME HPVC) competition in early April. Instead, the students learned how to ride the tricycle fixed in fully unstable mode, competed with it that way, placed 15th overall, and won the “Innovation Award”. [24]

Figure 23. The original bell crank with multiple tie rod attachment points.

After the competition, work commenced on a rider-adjustable bell crank. The first step was merely to add more tie rod attachment locations to the original bell crank, as shown in Figure 23. The rider must get out of the seat, support the vehicle with one hand, and move the tie rod from one attachment point to another with the other hand. It is certainly doable, and certainly not optimal.

Nevertheless, the consensus rider perception is that as the linkage geometry varies to reduce the instability, at the middle tie rod attachment point in Figure 23, the tricycle becomes easier to ride, although it requires more-pronounced countersteering. The presence of a cross wind or road camber feels weird at first, but this feeling fades as soon as the rider becomes accustomed to it.

Figure 24. Bell crank that can be adjusted by the rider.

Finally, in stable mode, with the tie rod attached close to the bell crank pivot in Figure 23, the tricycle will balance itself and support a rider, but this stability does feel very robust because the tricycle is not actually rigid. We will investigate automatically locking the bell crank in this mode, or something similar, to increase rigidity and improve the rider experience.

We created a new bell crank, shown in Figure 24, to enable the rider to adjust stability from the seat, while riding, that supports continuously variable geometry, and that enforces a circular arc trajectory for the tie rod ends so that actuation does not cause a change in seat height, which would require the raising and lowering of the rider's mass.

Of course, at neutral stability, the tricycle can be ridden or steered, but not both. Luckily, it only occurs at or very near a specific bell crank configuration, when the tie rod ends are about 100 mm (4 in.) apart, as suggested in Figure 10, and this can be easily skipped over in the transition from stable to unstable or back again.

4 CONCLUSIONS

The viability of a narrow-track, tilting, recumbent tricycle with rider-controllable stability has been demonstrated. It combines the best attributes of recumbent bicycles and rigid recumbent tricycles to eliminate major drawbacks of each. When the rider wants it to behave like a bicycle and lean into turns to balance the roll moment generated by centripetal acceleration with a roll moment generated by gravity, it can. When the rider needs it to behave like a rigid tricycle and remain upright when getting started, going slow, or stopped, it will.

Figure 25. Tricycle in action at ASME HPVC, piloted by UWM team member Tim Wegehaupt.

This provides new opportunities for two major groups of potential riders: people who cannot ride an upright bicycle because of some physical limitation and people who wish to commute in a narrow and fully-enclosed vehicle without the danger of a roll-over accident.

There is much future work left to do. We plan to create a new, fully-enclosed tilting tricycle, likely without a moving bottom bracket, for the 2020 ASME HPVC. We want to investigate ways to generate the force necessary to raise the rider's mass to take advantage of the opportunity to have different seat heights when in different modes. Finally, we are actively investigating commercialization of the technology.

Figure 26. Each of the authors making it go, in the order their names are listed on the title page.

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