Adding Arm Power to a Tilting Velomobile

by Wally Swarchuk, 24 November 2020

ABSTRACT

This article presents the design of an arm and leg propelled, four-wheeled vehicle comprised of front and rear swingarms and incorporating mechanisms for controlling vehicle inclination, as well as manual and free-to-caster steering devices for controlling vehicle direction.

By controlling the up and down movement of the rear swingarms, the operator controls the parallel inclination of the mainframe and wheels eliminating the need to put a foot down to maintain balance at stops and allowing the vehicle to be enclosed as an all-weather commuter.

Arm-cranking is performed with reciprocating hand-levers linked to a drivetrain, while tilt-control is actuated by the rider's hip shifting on a pivoting seat bottom and the reciprocating hand-levers when not arm-cranking. Both tilting devices are pivotally linked to the rear swingarms.

Manual steering is actuated by thumb-control levers, while free-to-caster steering is indirectly controlled by vehicle speed and inclination.

The complementary benefits of tilt-control, manual steering and free-to-caster steering allows the operator to engage in the arm-cranking when desired. The vehicle is propelled by legs only, arms only or equal cadence out-of-phase arms and legs.

Figure 1 -- Coupe style body with roll-down side windows

Figure 2 -- Vehicle frame with recumbent seat and arm cranking levers

DESIGN OVERVIEW

Enclosed human-powered vehicles suitable for commuting (velomobiles) are increasingly presented as a means to reducing congestion and pollution while increasing personal health outcomes.

Unfortunately, velomobiles have not gained wide acceptance as commuter vehicles due to a correlation of opposing structural and performance qualities. For instance, while low seat height has resulted in sufficient vehicle stability and low aerodrag, it is also associated with a more difficult entry/exit, as well as the need to see and be seen in traffic. Although a higher profile vehicle satisfies the concerns regarding visibility/safety, the concern for sufficient cornering stability of a narrow-track vehicle increases. Furthermore, while the outer shell provides low aerodrag in addition to weather and some crash protection, the added weight makes it more difficult to accelerate and to climb hills.

The recent development of dynamically stable velomobiles which tilt like a single-track bicycle when cornering is encouraging. Yet concerns regarding safety/visibility, entry/exit and additional power required to accelerate and climb hills remain. The design of this vehicle is aimed at addressing these remaining concerns.

DESIGN CONSIDERATIONS

The considerations or criteria used to make the decisions in designing this vehicle are:

Comfort and Safety

- The seat should be adjustable, support the upper body and spine, with a seat height similar to a compact sedan.
- The all-weather protecting cabin should be sufficiently windowed so the rider can see and be seen in traffic.
- Ease of entry/exit should be facilitated by a large cabin opening.
- Sufficient venting is to be built in.

Maneuverability

- The vehicle should be capable of a 180-degree "U"-turn on a typical residential street.
- Steering should provide precise maneuvering in tight spaces at slower speeds and for backing-up maneuvers.

Utility

- Sufficient, secure and easy access storage is to be built in.
- Track and body-width are to be restricted such that the vehicle is capable of passage on pathways and through doorways.

Speed

To help increase average speed the vehicle should incorporate:

- tilting when cornering,
- arm-cranking when accelerating and climbing hills.

Smooth Steady Ride

The cambering apparatus should be easily actuated and yet be sufficiently powerful to:

- mitigate the effects of strong side winds,
- maintain vehicle balance on slippery surfaces, throughout the range of speeds and at stops;
- work in concert with the steering system when traversing a slope,
- work in concert with steering and arm-cranking.

The suspension, steering and tilting systems should complement each other to:

- retain wheel alignment,
- minimize tire-scrub in bumps and depressions, and when cornering.

Fun Factor

- The design of the operating systems should strive for simplicity, intuitiveness, ergonomic comfort and dual-use whenever possible.
- The performance outcomes should contribute to the operator's feeling of confidence and fun.
- The design should consider aesthetics or curb-appeal.

METHODOLOGY

The design process was neither linear nor simple. Some of the criteria were tumbling loosely in my head from the start. Some I discovered through research, some through experimental trials, and many considerations used to design the tilting and steering systems emerged through failures and perseverance. It was truly an "emergent design".

My strategy generally followed this sequence. First, I sketched an idea out on paper, then made a wood or cardboard model. If the idea seemed promising, I turned to my hobby welder, fabricated the mechanism, attached it to my operating trike or quad, and tested it out. The real-life test would invariably pinpoint specific actions/reactions not anticipated or incorrectly assumed. As the years passed I grew accustomed to the following narrative -- scrap that idea, change this construct, redesign those components.

Throughout the design, build, test, rebuild sequence I recorded the operational attributes of the alternative designs. This proved to be valuable. At least, I had a qualitative and sometimes quantitative measure of my progress.

The design process was guided by two questions: 1) Have I considered all reasonable alternatives? and 2) What happens when I invert, reverse, or turn the idea/construct inside-out?

I discovered that changing one element in a mechanism can generate new and reasonable alternatives in other mechanisms as well. The seemingly endless process of discovering new reasonable alternatives is what my wife affectionately calls NERD (Never Ending Research & Development). By striving to attain the "best practice" model of each mechanism, I have been highly successful in dragging this retirement project well into its second decade.

Thankfully some constructs proved to be far more successful than others and the "proof of concept" vehicle described in this article consists of the components which survived the test of time, and escaped the cannibalization inherent in the "scrap that idea and rebuild sequence".

DUAL DRIVE SYSTEM

Commonly, two variations of arm-cranking are incorporated into single and multi-track vehicles. Either rotary hand cranks are placed in front of the operator, or reciprocating levers are located to each side of the operator. In spite of the efficiency of the former, I chose the latter for several reasons.

Many benefits are realized by locating the levers to each side. The operator's forward view is unrestricted as is his access to the seat. Underarm venting is facilitated and applying force along the shallow arching path of each lever handle is both intuitive and ergonomic. Since levers do not require rotating joints essential for hand cranks, the cable linkage for brakes and gear selection is less bulky and complex. In addition, linkage from the crank spurs (see Fig. 3) to the crank arms and back to the mid-drive axle can be placed under the driver's seat resulting in a compact non-intrusive drivetrain providing sufficient space within the cabin to comfortably actuate the hand-cranking levers.

Unfortunately, reciprocating levers have inherent problems. Rotational lockup can occur when the pivotal swing of the crank spurs and the rotational movement of the crank arms are at their

extreme fore and aft positions (dead spots). Fortunately, by altering the crank arms from their usual 180 degree offset as illustrated in Fig. 3, rotational lockup is avoided.
Another problem is reciprocating levers will not always rotate the crank arms in the desired direction resulting in rotating the mid-drive sprocket in freewheel. My solution was to fasten a freewheel sprocket onto the hand-crank axle. Engaging the lock lever with that freewheel sprocket (see Fig. 3) ensures that arm cranking rotates the mid-drive axle forward, while disengaging the sprocket permits the vehicle to be maneuvered backwards.

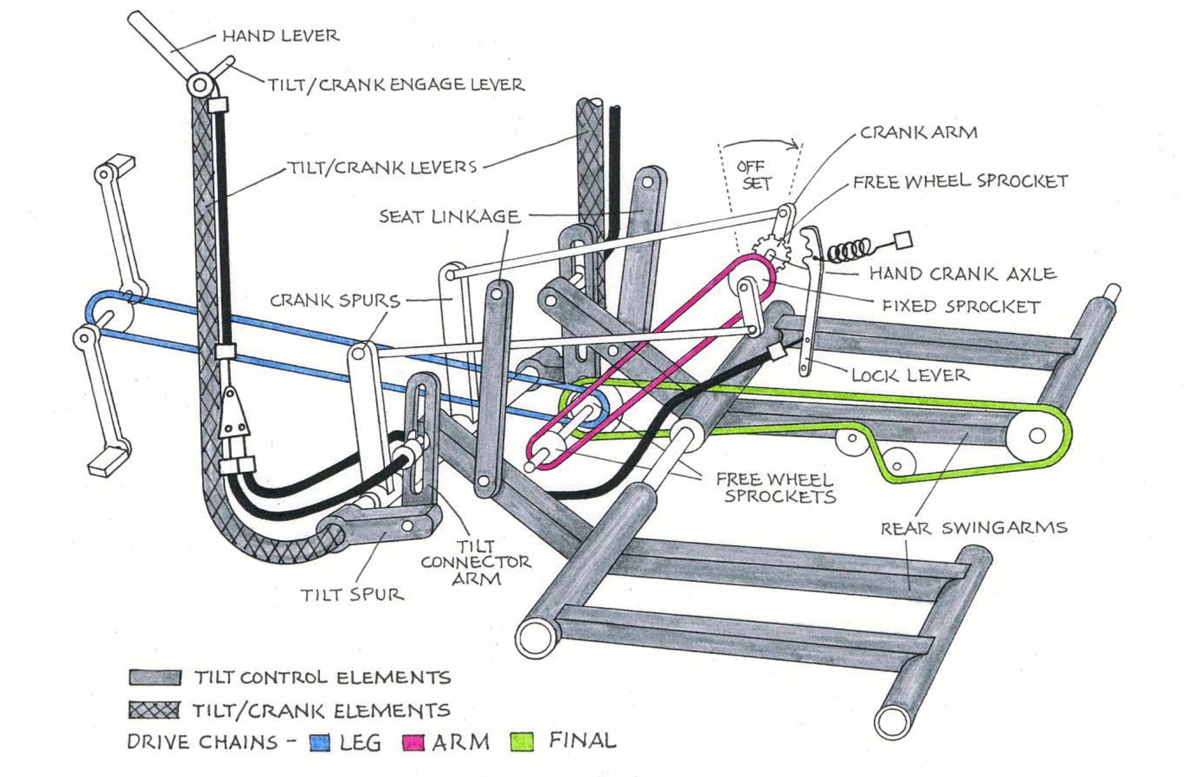

Figure 3 -- Schematic of dual drive system and tilt control elements

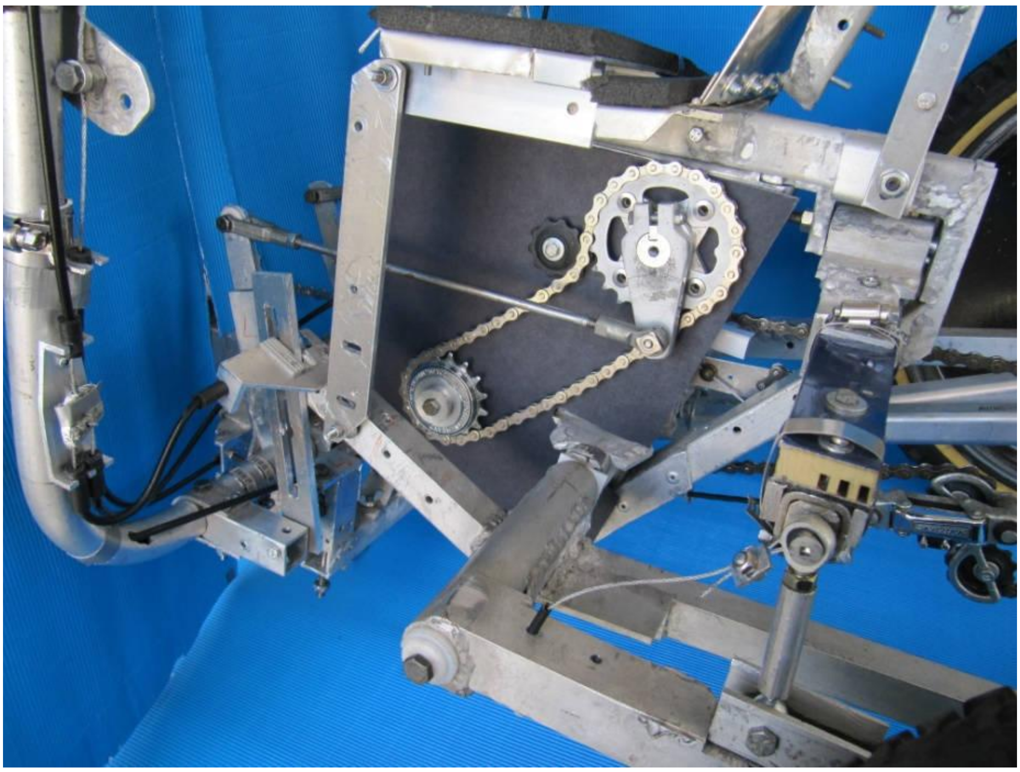

Figure 4 -- Under the seat drivetrain and tilt control elements

Fortunately, the cable linkage controlling the lock lever could be twinned with a cable which converts the cranking levers into tilt-control levers, thus avoiding additional controls and procedures.

DIRECT TILT CONTROL

Experiments on different test vehicles and my research focused on deciding whether to integrate the arm-cranking mechanism with an arrangement in which steering directly controls vehicle tilt, or with an apparatus which controls roll or tilt to indirectly control steering. The former is known in the art as STEER TILT CONTROL, while the latter arrangement is called DIRECT TILT CONTROL. I chose to incorporate Direct Tilt Control.

By choosing the Direct Tilt Control arrangement I hoped to fulfill the criterion of a smooth, steady ride in the contexts of travelling in gusty side winds, on slippery surfaces, when cornering at speed, as well as maneuvering slowly in limited space areas. Examples of larger, heavier motorized tilting vehicles which utilize the resistance of two separated surface-engaging wheels to control vehicle inclination with powered actuators suggested to me that it might be possible to design a much smaller, lighter vehicle incorporating a tilt apparatus of sufficient mechanical advantage to control vehicle inclination by human power alone. This design goal became the most challenging part of my project, along with the design of the steering systems. My other reason for choosing Direct Tilt Control will appear in the STEERING section of this article.

Alternative designs of Direct Tilt Control were assessed. A two-way longitudinal and lateral axle mechanism designed to combine a side-to-side motion with the fore and aft reciprocating levers was tested. After several variations of this design, I concluded that it was impossible for me to obtain sufficient mechanical advantage without the levers inclining more than the vehicle mainframe, making it difficult to arm crank within the confines of the cabin.

After rudimentary tests showed that my hand-squeeze strength was approximately six times greater than my side-to-side push-pull force of both forearms, I persevered through a few attempts at variant hand-squeezing devices with diverse mechanisms pivotally connecting the vehicle frame with the rear swingarms, front swingarms, or both. I achieved reasonable success, but each time the combined actions of hand-squeezing, thumb-controlled steering, plus hand-cranking took the fun out of the ride. A more simple design was needed.

Figure 5 -- Clam door opening for entry/exit

Currently, two constructs are embodied to pivot rear swingarms up and down to produce a parallel inclination of vehicle mainframe, cabin and wheels. The pivoting seat bottom is activated by the operator's hip movement or subtle weight shift, and the arm-cranking levers can be converted to function as tilt-control levers by activating a small lever located on the handle of each of the hand levers to "lock" the tilt connector arm with a rear swingarm (see Fig.3 and Fig.4).

When both tilting mechanisms are engaged one serves to generate vehicle tilt, while the other can counter or limit the degree of tilt. It feels like I'm "in control" of a robust and complementary Direct Tilt Control system.

STEERING SYSTEMS

My decision to design an apparatus which first controls roll or tilt to indirectly control steering was based on my research into free-to-caster steering. I reasoned that because free-to-caster steering responds to the tilt and speed of the vehicle ,it would provide a kind of "hands-free" steering at higher speeds. Thus, instead of tilting and steering, my hands could be engaged in tilting and arm-cranking with steering automatically provided. At slower speeds a manual steering system would be incorporated for precise steering in limited space areas and for maneuvering backwards.

Embodiment & Operation of Manual Steering

When the operator engages the left thumb-lever to turn right, the cable linkage rotates the steering shaft and knuckle to the operator's right (clockwise) forcing the Ackerman arms of the steering knuckle to move the posterior portion of the pivot blades to his right, while the anterior portion of the blades force the hubs and wheels into a right-hand turn via the tie rods. This 'steer right - turn right' and vise versa operation is also referred to as 'simple steer', which can be applied at any degree of tilt, whether moving forward slowly or while stationary.

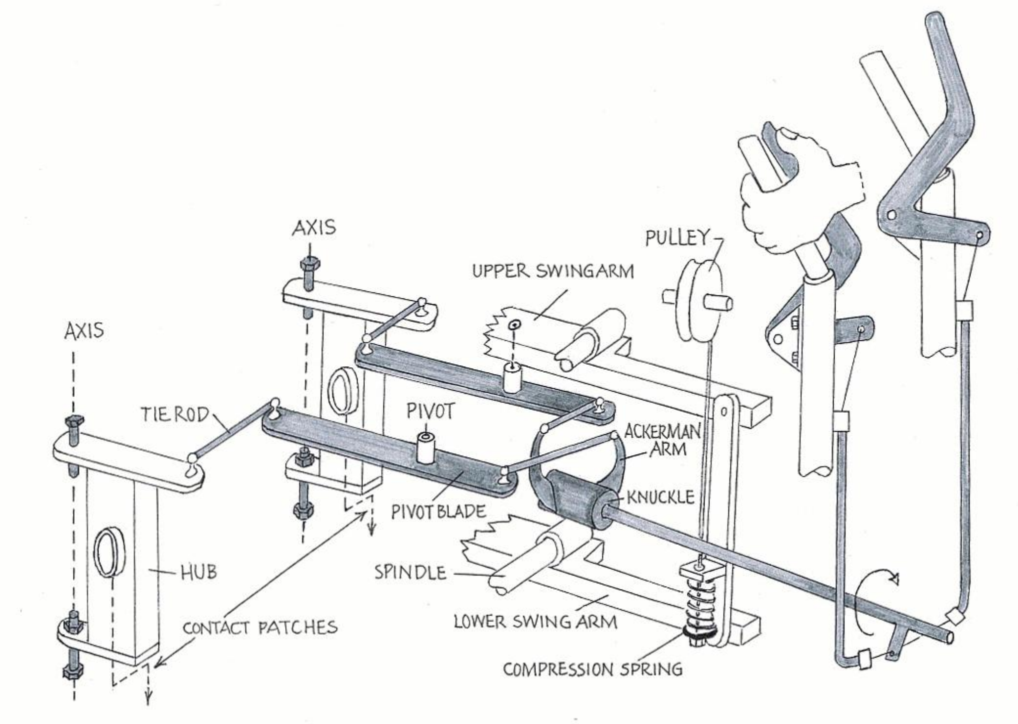

Figure 6 -- Schematic of steering systems

Embodiment of Free-to Caster Steering

Free-to-caster steering relies on steering input to come from the tilt and forward movement of the vehicle. In other words, from the drivetrain and tilt-control apparatus already described. My design also includes the embodiment of caster wheels within a hub-centered construct.

Each hub contains vertically aligned bolts to which the upper and lower front swingarms are pivotally attached creating a zero degree rake-steering axis (viewed from the side of the vehicle). Each wheel is fastened to a flange and axle such that both wheel and axle rotate together, and the axle rotates within the bearing-sized pipe of the stationary hub (see Fig.6 and Fig.7).

The non-rotating hub is similar to a fixed "axle box" for a railway car in that it houses the rotating axle and, because the axle trails the vertically aligned steering axis, the hub and wheel function as a caster wheel.

After numerous builds and rebuilds this design survived the test of time because of its ease of construction and the following structural and performance features. Since the steering axis is aligned with the center line of the tire and because the axle bearings equally straddle that centerline, this design provides sufficient weight and lateral force-bearing capacity allowing for light-weight component parts arranged in a slender hub and shallow-dished wheel. The zero degree rake provides light touch simple steering with a sensitive response to caster steering. In addition, when the hub is pivotally attached to the upper and lower swingarms, front-wheel suspension travel remains in the "plane of inclination" with the steering axis to minimize tire scrub throughout suspension travel in bumps, depressions and cornering.

Figure 7 -- Hub, tie rod, and pivot blade beneath swingarm

Operation of Free-to-Caster Steering

When the vehicle is stationary, tilting the mainframe and caster wheels has no impact on the steering linkage because the swingarm spindles are directly above and below the Ackerman arms and rods (see Fig.6). Consequently, the steering knuckle does not rotate and although the caster wheels do tilt in a parallel plane with the vehicle mainframe, they do not pivot on their axis to change steer angle until the vehicle is moving forward and tilting.

When moving forward the Direct Tilt Control apparatus produces a parallel cambering of the vehicle mainframe and steering axis. Now, because the axles trail the steering axis, the forward rotating front wheels begin to steer in the direction of the inclination. As speed and inclination are altered, the steer angle adjusts impacting the movement of the tie rods.

In free-to-caster, the impact of speed and tilt proceed upwards from the caster wheels through the steering linkage to the thumb-control levers which I can feel moving freely back and forth. As long as the vehicle is substantially upright at speed, I can gently nudge the levers to maintain directional control without having to adjust vehicle tilt. These tiny simple steer inputs proceed from the thumb-levers downwards through the steering linkage to minutely alter the steer angle of the front wheels. The same linkage serves both steering systems which are permanently available.

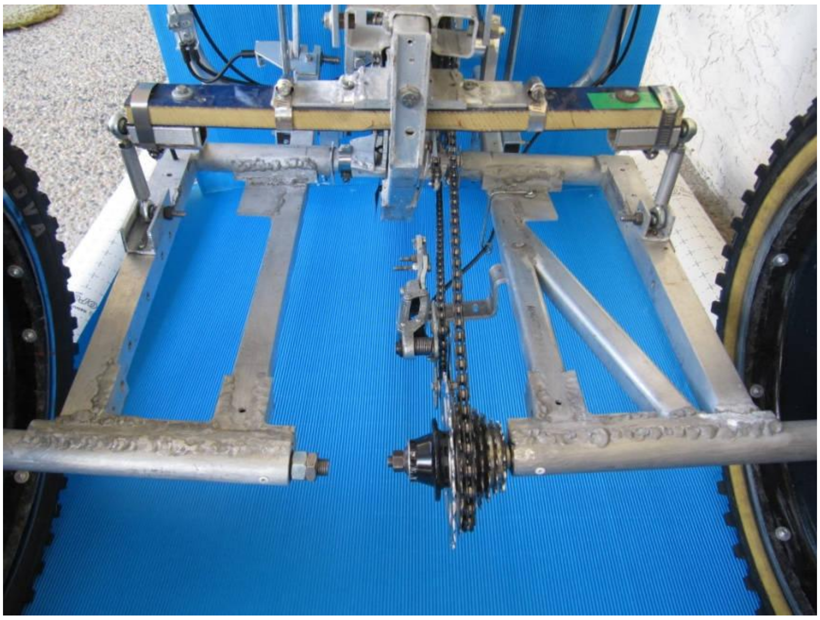

Figure 8 -- Rear swingarms with section of a downhill ski for suspension

HOW THE DRIVE, TILT & STEERING WORK TOGETHER

To aid understanding of the following, refer to Figure 3.

When pedalling forward, the fixed sprocket on the pedal axle rotates the freewheel and fixed sprocket(s) keyed on the right side of the mid-drive axle, causing the final drive chain to rotate the rear axle and wheel forward. The freewheel sprocket on the mid-drive axle permits the operator to pedal backwards to obtain the desired position to start pedalling.

For tilt control, each hand-lever is linked to a rear swingarm via a fixed tilt spur and a pivoting tilt connector arm. A spring loaded bolt temporarily locks each slotted connector arm with a rear swingarm. When the vehicle is stationary, this arrangement provides a one-sided "lean lock" feature until leg-cranking begins rotating the mid-drive axle forward. Now the freewheel sprocket, keyed to the left side of the mid-drive axle, is free to rotate forward or to freewheel in reverse. This liberation (forward/reverse rotation) of the arm-cranking drivetrain facilitates the fore and aft movement of the hand-levers to control vehicle tilt. As long as the leg-cranking drivetrain is rotating faster than the requirements of moving the hand-levers to control vehicle tilt, there is no conflict between tilt control and the now passive arm-cranking drivetrain, except that vehicle inclination (currently 12 degrees from vertical) is limited by the range of movement of the arm-cranking drivetrain linkage.

Pulling the right hand-lever back while pushing the left hand-lever forward results in tilting the vehicle to the right, and vise versa. Holding the levers stationary at any position results in holding that degree of tilt, which is very useful when traversing a side slope.

Manual steering is performed at slower speeds and especially in tight areas. Free-to-caster steering is designed for higher speeds and especially when entering sharp corners because the operator <u>must</u> use the Direct Tilt Control to <u>first</u> tilt the vehicle in order to avoid applying counter steer. I will expand on this in the Persistent Issues section of this article.

For combined arm-leg cranking each slotted tilt connector arm is disengaged from its rear swingarm, allowing it to slide freely up and down on the spring loaded bolt which is still connected to that swingarm. This disengagement releases the hand-levers from their tilt control function and permits them to function as hand-cranking levers. Now, the reciprocating movement of the hand-levers and crank spurs generates the rotary movement of the hand crank axle. In turn, the fixed sprocket (keyed to the hand crank axle) rotates the freewheel sprocket (on the left side of the mid-drive axle) forward to provide arm-cranking propulsion. The two freewheel sprockets on the mid-drive axle provide the flexibility of arm-cranking only (right sprocket spins freely), leg-cranking only (left sprocket spins freely), or arm-leg cranking (both sprockets are forced to rotate forward).

Equal-sized fixed sprockets on the hand and leg crank axles ensure equal cadence, while equal-sized mid-drive freewheel sprockets enable the operator to synchronize the arm-leg drive trains to maintain efficiency of the dual drive system, Mechanical crickets (audio clickers) are attached to the left pedal crank, as well as to the right crank arm of the hand crank axle. Thus, when my left foot nears the end of the "effective force" portion of the leg-cranking cycle, my right hand is pushing to enter the "effective force" portion of the arm-cranking cycle. This equal cadence out-of-phase arm and leg-cranking is most efficient when the clicking sounds are synchronized, which is beneficial when riding up a long hill.

During arm-leg cranking, tilt control is managed solely by the pivoting seat bottom's linkage with each rear swingarm (The back-rest does not pivot.). Since there is no mechanical means for applying a counterforce to avoid over-tilting the seat bottom, the combination of DTC and minimal simple steer measures can be applied as long as the vehicle is substantially upright, which is often the case when accelerating and climbing hills. If manual corrective steering is not required, then the operator can rely on free-to-caster steering while arm and leg-cranking up that long hill.

VEHICLE SPECIFICATIONS

<u>Vehicle Dimensions</u>
Height .... 145 cm
Width............................ 75 cm
Length .... 235 cm

Cabin Opening (access). 70 cm
Seat Height 50 cm

<u>Secure Storage</u>
(potential) 130 + litres

<u>Vehicle Weight</u>
Cabin ....13 kg
Frame..................... 36 kg
Total Vehicle .... 49 kg

<u>Weight Distribution</u>
Front........................ 45%
Rear.................. ...... 55%

<u>Suspension Travel</u>
Front Wheels.................. 4 cm
Rear Wheels .... 10 cm

<u>Wheel Details</u>
Track .... 65 cm
Wheel Base................. 165 cm
Rim Size .... 406 mm

<u>Turning Circle</u>
180 degree u-turn within 7 m

The illustrations, photos and vehicle specs can be examined to see how the vehicle measures up to the design criteria of comfort and safety, maneuverability and utility. This section will provide a qualitative assessment of how the vehicle measures up to the features of a smooth, steady ride and the fun factor.

<u>Arm and Leg Cranking</u>

When force is exerted on the arm-cranking levers the ride feels stable. The more force, the better it feels. When travelling down a slope and not accelerating the ride feels less steady because without the propulsion resistance, the cranking levers feel liberated in their fore and aft movements. This is when I convert the cranking levers into tilt control levers and continue with leg-cranking only. The conversion to legs only and back again is accomplished by simply releasing or engaging the tilt/crank engage levers.

Along straight narrow cycle lanes arm-leg cranking can result in an uncomfortable moment if I unexpectedly tilt the seat bottom too much, which impacts my directional control. Because the seat bottom is the single actuator for tilt control when arm-cranking, and because free-to-caster steering responds slowly to vehicle inclination, I developed the technique of applying minimal inputs of manual steering which produce rapid, yet comfortable, directional control at higher speeds as long as the vehicle is substantially upright and the tilt control apparatus keeps it that way.

Although my goal of total "hands-free" steering has not been realized, the complementary effects of Direct Tilt Control with free-to-caster steering, supported by tiny manual steering inputs, provides the directional control required.

When travelling slowly, I can combine arm-leg cranking with manual steering to complete a 180-degree U-turn on a roadway. However, arm-leg cranking is unnerving on unpredictable terrain because tilt control is limited to the pivoting seat bottom, and I am without the counterforce of the tilt levers to manage and limit the tilt of the vehicle.

As expected, free-to-caster provides smooth, stable steering control when tilting into corners, yet I often find myself holding the levers steady instead of cranking throughout a right-angle corner. Perhaps it is part of the learning curve to feel comfortable with the aggregate actions of watching for traffic, tilting, foot cranking as well as arm cranking at speed.

<u>Leg Cranking Only</u>

Not once did I have a coordination difficulty when converting from arm-leg cranking to legs only, or vise versa. Probably because I must consciously decide and thus I am prepared for the motion of cranking or tilting.

Operating two complementary tilt mechanisms allows me to push and limit vehicle tilt simultaneously providing a stable, steady feeling to the ride. The steadiness feels consistent regardless of the force placed on the foot cranks or vehicle tilt or speed. Travelling slowly, manual steering provides precise control, permitting me to drive through a 80cm doorway. When traversing a slope, I adjust the tilt to upright and apply simple steer to maintain my desired direction. Travelling on a significantly crowned road requires either a slight manual steer touch to maintain my straight ahead direction or to let the vehicle run slightly tilted or perpendicular to the road surface.

With both tilt control devices at play I get the sense that I'm in control within the confines of the bike lanes, when riding in gusty cross winds, on loose gravel, on bumpy terrain and when cornering at speed.

<u>Leg Cranking Only & Cornering At Speed</u>

It feels good. My confidence in the dual tilting mechanisms and the consistency of the free-to-caster steering at speed in corners is solid. There is no issue with tire scrub in either steering systems. Since I relocated the seat linkage to reduce the tilt, I no longer sense that the seat bottom is still tilting more than the vehicle, and no lateral forces are felt when cornering at speed.

To ensure that I tilt <u>first</u> into a 90-degree corner at speed, I developed the habit of lifting my thumbs from the manual steering levers, tilt into the corner, then apply manual steering coming out of the corner. It feels good. It is the most fun part of the ride. I realize that in this singular situation, applying manual steering amounts to counter steering (steer right to TILT left). How ever, to the rider this select maneuver feels like simple steer is being applied. Consequently, no unconsciously trained skill is required and no double thinking about simple vs counter steer is necessary.

I was surprised that using my left thumb to turn right with simple steer proved to be more intuitive when coming out of corners at speed as well as for precise maneuvering at slower speeds.

<u>Leg Cranking Only, Cornering and Braking</u>

Currently braking is limited to both front wheels with no noticeable brake dive.

Some time ago, in a cornering and brake test, the inside front axle (12mm T6061 Aluminum) snapped in half. I believe it was the result of too much lateral play in the front swingarms and uneven brake adjustment. I adjusted the brakes and replaced the axle but have avoided extreme testing, convinced that steel axles, hydraulic brakes and machined bushings on the swingarm spindles will prevent a repeat. I am currently using cut-up PVC irrigation pipe for the bushings as it is just a "proof of concept" model.

I should also confess that all of the mechanisms and frame parts (other than fasteners, rod ends, donor-bicycle parts, axles and bearings) were fabricated primarily from recycled aluminum with just four power tools; a bench saw, a drill press, a hobby welder, and a router attached to a two way cross slide vise to make the mould for the fiberglass wheels.

Although the wheels are not well-centered or true, the swingarm suspension allows me to achieve 26 km/hr before the wobble and hump of all four wheels proves to be too distracting and inefficient.

Persistent Issues

After alternative devices were constructed to retain alignment of the caster wheels when maneuvering backwards, I finally discovered that in my design the distance from the steering axis to the wheel axle (trail) must not exceed 42 percent of the distance from the steering axis to the pivotal attachment of the tie rod.

Unfortunately, not all of the issues involved in maneuvering backwards have been resolved. Since I use a single controller to disengage the freewheel sprocket on the hand crank axle (see Fig. 3) while simultaneously engaging the hand-levers with the tilt system, the reverse rotation of the drivetrain causes the vehicle to sway from side to side. I have learned to accept this design flaw because having separate controllers was even more of a nuisance, since I kept forgetting which controller to engage or disengage.

A constant issue beleaguering my design decisions involved pursuing my functional goals of tilting, smooth & steady ride, etc. while adhering to the criterion of structural simplicity. And still, I ended up with two drive systems, two steering systems and two mechanisms to control tilt. Many observers have asked "Why is it so complicated?" Here is my answer.

Sometimes there is a trade-off between structural and operational complexity. For instance, tilting and steering is structurally less complex in a STC vehicle, but more complicated to operate because the technique of counter steering is required at higher speeds. Counter steering (steer right to TILT left) can be unnerving, if not dangerous, in a split-second avoidance maneuver. Thus, I opted for DTC because it offers fail-safe tilt control, even on icy surfaces, and makes free-to-caster steering possible which facilitates hand-cranking. When riding my velomobile, I simply control vehicle tilt at all times and the vehicle appears to know what to do (caster steering) until my speed slows to the point where I apply simple steering. It all feels seamless and natural and simple.

Yes, the tilt control mechanisms add complexity and weight but provide dynamic and static stability required for smooth, steady riding and stopping. And, since the same linkage serves both steering systems, the overall complexity for tilting and steering is, I believe, acceptable.

What about arm-cranking? I started this project as a human-power purist, and challenged myself to find innovative ways to make a dual-drive system workable and beneficial. Placing the arm drive mechanisms under the seat and incorporating dual-use hand-levers for cranking and tilting makes it workable within the confines of the cabin. However, the unresolved issues of maneuvering backwards and the limitation on the range of vehicle tilt still remain. Is the added complexity of arm-cranking worth it? That answer is provided in the FUTURE DEVELOPMENTS section of this article.

ACKNOWLEDGEMENTS

Throughout this project, I relied on internet searches for general, technical and research information. Not surprisingly, I found myself mirroring the trending foci of individual projects and commercial ventures. As trike frames became increasingly enclosed for aerodynamics and weather protection, I also ventured into "veloland" and the quadricycle design, but held onto my early goals of complementary tilting and steering with arm cranking.

In addition to obtaining technical information which advanced my design, my searches motivated me and, therefore, key contributions will be acknowledged.

Thanks to Hepheastus of the Left-handed Cyclist blog for establishing the criteria for designing a practical human-powered commuter vehicle as well as providing the background of various vehicles and how they measure up to each criterion.

The web pages on Hub-Centered Wheels of Rick Wianecki's "Leaning Trike Project" helped advance my goal of complementary tilting and steering which had been hampered by the compromises inherent within my center-point-steering arrangements.

Numerous contributors have advanced the dialogue on free-to-caster steering and it was Phillip James' TVA article "Tilting Vehicle Suspension Systems" illustrating the benefits of "plane of inclination" suspension travel which led me to seek alternatives to dual front wishbones. That alternative emerged upon witnessing the possibility of incorporating manual steering linkage with dual front swingarms on a tilting vehicle.

Thanks to Jacek Skopinski for images of the EV4 tilting electric scooter's dual front swingarms absorbing uneven terrain with manual steer controls.

By attaching my zero-degree raked hub and caster wheel to dual front swingarms, and by re-designing the steering linkage, I retained Ackerman steering geometry with simple steer and free-to-caster steering. By attaching light-weight compression springs to the cable linking the posterior ends of the front swingarms, I could now obtain suspension travel in the "plane of inclination", in addition to asynchronous pivoting of the swingarms to accommodate vehicle tilting (see Fig. 6).

Finally, research studies convinced me that some contribution and duration of arm-cranking is worthwhile, especially when out-of-phase arm-cranking supplements the effective-force deficit (dead spots) of the leg-cranking cycle, while smoothing out the power flow to the drive wheel(s).

FUTURE DEVELOPMENTS

I plan to use the comments or suggestions regarding my proof-of-concept vehicle to advance the design and development of a prototype that is readily converted from a quad into a three-wheel delta and vise versa. For instance, by substituting a modified steering knuckle, a modified tie rod, a single sided swingarm, and by attaching the non-rotating hub and caster wheel assembly to the single swingarm, the delta model will retain suspension, as well as manual and free-to-caster steering guided by Direct Tilt Control. Except for a different nosecone, all other components including the cabin and tail sections, are interchangeable (see Figure 9). Naturally, everything will be streamlined and upgraded with appropriate materials and machined parts.

I'm calling my quad model "Little Douce Coupe" meaning sweet little coupe, and the three-wheeler will be called "Delta Douce Coupe".

Figure 9 -- "Delta Douce Coupe" with single sided swingarm

Figure 10 "Quad" parked next to a compact sedan

The major difference between the prototype and proof-of-concept will be the absence of arm-cranking. Why not arm-cranking? For me, at my age, arm-leg cranking did not measure up to the criterion of a smooth, steady ride contributing to my feeling of confidence and fun to the extent that leg-cranking only has done. The added complexity and weight of the dual drive system does not appear to be worth it. By removing the arm-cranking drive train, the backing-up and tilt constraint issues will disappear. In addition, when both tilt control mechanism are in play, the added stability will be permanent. Finally, the complexity at the user-end of the steering linkage can now be reduced. By dedicating one of the hand-levers to control manual steering via direct pivotal linkage to the steering shaft, the thumb-control levers and cables can be removed. Since issues arise primarily between arm-cranking and tilting, perhaps arm-leg cranking can be further advanced in less complex non-tilting velomobile designs.

Another significant change involves my plan to remove the entire leg-crank drivetrain and replace it with a Series Hybrid Drive System. Two important attributes of the Series Hybrid system are, (1) the simplicity of the electronic drive (no chains, no derailleurs or gear box), and (2) the flexibility of designing the vehicle that the electronic drive is placed into. In my case, without the need for the final drive chain, I can simplify both rear swingarms and install a single-sided, all-axle hub motor onto one of the swingarms. The pedal generator of the Series Hybrid Drive is human powered, and the vehicle's tilt will continue to be mechanically controlled by human power.

I would like to acknowledge the research and development of the Series Hybrid Drive System conducted by Andreas Fuchs (Berne, Switzerland). Thanks to his pioneering work, the complexity of my tilting velomobile can be significantly reduced.

And so, the "emergent design" of my project continues. Looking back at the cumulative results of my design process, it appears that some novel elements and constructs have emerged. I believe the design of the swingarms (linear portions fore and aft of their pivotal attachment) which provide weight-bearing leverage, as well as facilitate synchronous swingarm movement for suspension travel in the "plane of inclination" and asynchronous pivoting for controlled vehicle cambering, is novel.

Another novel arrangement could be the design of the non-rotating front hub with caster wheel, the design and placement of the steering knuckle and steering linkage which accommodates the up and down movement of the dual swingarms while providing Ackerman steering geometry in both manual and free-to-caster steering.

I anticipate that commuter velomobiles will be perceived by more people as a safe, fun, practical and healthy form of personal transport. I am grateful that this publication provides the research data and profiles the innovations which keep advancing the technical knowledge to make it happen.

REFERENCES

Astrand, P.O. and Saltin, B. (1961) "Maximal Oxygen"
Journal of Applied Physiology 16(6) 977-981

Foale, Tony (2000) "Experiments with Rake & Trail Variations"
https://motochassis.com/articles/experiments-with-steering-geometry/

Fuchs, Andreas (2008) "Series Hybrid Drive-System: Advantages for Velomobiles"
Human Power eJournal 5 (15) https://hupi.org/HPeJ/0015/0015.html

Powell, Richard an Robinson, Tracey (1987) "The Biometrics of Power Production in Combined Arm-Leg Crank Systems"
Human Power 6(3) 8-10 http://www.ihpva.org/HParchive/PDF/21-v6n3-1987.pdf

THE AUTHOR

Wally Swarchuk (litldoucecoupe @ gmail.com) resides in Kelowna, British Columbia, Canada. He is a retired educator who has written Ministry of Education curriculum with an emphasis on problem solving and critical thinking. He is currently an advisor for curriculum development with the Center for the Advancement of a Steady State Economy. His life-long passion is white-water canoeing and wilderness camping. At age 75, he can still ride a bicycle backwards!