A Preliminary Design of a Land Yacht with an Auxiliary Electric Motor

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The main goal of this work is to study the integration of an auxiliary electric propulsion system in a land sailing vehicle destined to recreation. By making the vehicle a hybrid it is expected to make it more appealing to potential users.

Initially, it is exposed the relevance of this thematic, being followed by a market and patent research with the objective of knowing the existent options in terms of components that may be explored in this project, namely in what concerns the electric motors, batteries and controllers. Based on the information gathered different concepts of vehicles were generated. Utilizing a set of selection methods these concepts were reduced to a single one to be studied in detail. In a second stage it is done the preliminary structural design of the vehicle, namely the static analysis of the chassis in different load situations, the study of the natural modes of vibration and the analysis of the bolted joints. Finally, it is made the study of the electric circuit to be implemented.

In conclusion, the implementation of electric motors in this type of vehicles is a current topic that begins to be explored by the main brand in the sector, and although this integration brings along some challenges it also allows to benefit from advantages, one of the most relevant being the possibility of using the vehicle under a broader set of atmospheric conditions, smaller sail, etc.

**Keywords:** Land Sailing, Electric Propulsion System, Concept Generation and Selection, Mechanical Design

**Introduction**

The main challenge of this work is to study solutions to transform a regular land yacht in a hybrid vehicle. In the last few decades there has been an increasing effort in the research and development of vehicles that use non fossil fuel based sources of power, being one of the main strategies the use of electric and hybrid vehicles to substitute the conventional ones.

The advent of the electric vehicle is one of those cases where a particular achievement is responsibility of several different people working separately and making small contributions during a long period of time. Although many prototypes and
improvements were made in the years before, only in 1884 appeared the first production electric car [1]. In the beginning of the XXI century there was a revival of the interest due to economic and environmental factors, as well as technical progresses, and they are now seen as a key technology for the future of human mobility. The land yacht is an example of a vehicle that does not use fossil fuels and that is relatively unknown: they are wind powered, usually wheeled land vehicles typically with a single occupant, which are operated in flat areas where wind speed is moderate to strong, as a leisure activity. In this project, the main goal is to design and incorporate an electric propulsion system in one of this wind powered vehicle, allowing to utilize the vehicle in atmospheric conditions in which is impossible or difficult to do with the conventional models. The idea is that the power generated by the electric motor would for significantly compensate the lack of thrust impinged in the sail in low wind situations. Even though this is a project dealing heavily with matters such as electric motors, circuits and controllers, the primary concern is to obtain a structurally sound solution to accommodate this equipment and transport the occupant safely.

It is recognized it would be important to actually build a working prototype of the vehicle and experimentally assess the viability of the electric hybrid land yacht projected. However, that exceeds the ambit of the present document mainly due to time restrictions in this work and for that reason would be an interesting topic for future researches.

**Market and Patent Research**

In order to proceed with the generation of concepts, in an initial stage is necessary to conduct a research about the options available for the different elements of the system.

The simplest and most economically viable solution for the vehicle is to use a DC motor. These can be classified in brushed or brushless (figure 1). For this project brushless motors have more adequate characteristics [2].

![Figure 1 – Brushless (left) and brushed motors [3]](image)

Bearing in mind the characteristics of the application, namely the approximate power interval it is anticipated to be required to assist the wind propulsion, it is expected that the motors found in electric bicycles (as well as their control systems) might be an appropriate solution to the problem: they are small DC motors used to complement the main power source in light vehicles that carry a single occupant and move at moderate speeds, all of which are aspects shared with land yachts.

In general terms, it is possible to classify the different types of electric bike motor systems in the following categories [4], [5]: hub
motors, which can be classified in direct drive or geared (figure 2), mid drive, shaft drive and friction drive motors.

![Geared hub motor (figure 2)](image)

Figure 2 – Geared hub motor [6]

Considering the characteristics of each of these types of motors, it was possible to exclude the latter two kinds.

In what concerns the type of battery [7], [8] the research done focused in the following: lead acid, lithium (figure 3), nickel cadmium and nickel metal hydride. It was possible to eliminate the last two kinds based on their features.

![Typical e-bike battery (lithium-based) - adapted from [7]](image)

Figure 3 – Typical e-bike battery (lithium-based) - adapted from [7]

Similarly, controllers from electric bikes may also be used in this project. There are two different types of control philosophies used on e-bikes: throttle (manual) or pedal assist, while some models allow to choose between both (which is known as hybrid power control). In the first way of activating the electric propulsion the rider operates a switch or paddle that allows to turn it on and off (so it can turn into a fully electric vehicle) and to select the intensity of the motor delivery. The output of the motor remains independent of whether the rider is pedaling. On a pedal assist type bike (also known as half-assist), the motor automatically provides power when the rider pedals and only in this situation, based on the information gathered by multiple sensors [9].

Relatively to structural solutions for the land yacht, the structure of the vehicle has already been studied in a previous thesis [10], on which the present document partially intends to build upon. It is going to be considered the main structure from that reference (from now on designated structure A). It can be seen on figure 4.

![Base chassis structure A for the hybrid kart project [10]](image)

Figure 4 – Base chassis structure A for the hybrid kart project [10]

In order to establish a comparison with the previous chassis it was chosen the standard Blokart model (structure B), which nowadays is the most sold land yacht. The mentioned chassis are the foundation of the structural part of every concept studied in this project, but several modifications are introduced: they are the starting point but the final arrangement may involve major changes whenever the conducted analyses reveals such necessity.
Similarly to products existing on the market, issued patents dealing with this type of products may provide crucial information to complement the concept generation process or to better understand certain technical details of the components under consideration and their legal restrictions. For that reason, a brief patent research was conducted. Among the inventions found was a wind driven vehicle with electric motor assist [11] that shares several features with the vehicle to be designed in this work.

Once the important characteristics of the components were defined it was made a specific exploration of the commercially available options for motors, batteries and controllers. Unlike the initial generic market research, which had the goal of investigating the different existing technologic variants of the components (in order to make an assessment of what could be used in the vehicle), this stage of the project had the objective of finding suppliers for the constituents needed, to determine whether to select a complete bicycle, a conversion kit or separate components and to know the prices.

### Concept Generation

Based on the components found on the market research, it was conducted a process of generation of concepts centered on a set of generic guidelines according to which is possible to consider the vehicle could satisfy costumers’ needs as defined for this work. Structures A and B were combined with several electric components in different configurations and positions, resulting in a total of 24 concepts. In order to reduce the number of concepts to consider, it was first made an initial screening based on considerations of some of these concepts being clearly inferior to others. They were reduced to 12 concepts, and at this point it was feasible to use the selection methodology.

As a reference for the selection process it was used a product from the company Blokart (figure 5) that consists in an addition to their land sailing vehicles: a wheel with an incorporated hub electric motor and corresponding battery pack, controller and throttle [12]. It is therefore a product that aims to solve the same identified shortcomings of land yachts and that seems in a first analysis to follow the same product generation steps (namely having as a base the technology found on e-bikes and adapting it to the land yacht).

![Figure 5 – Blokart electric motor [12]](image-url)

The concepts under examination were compared to the reference and rated according to their performance in each of the selection criteria in relation to it. From this procedure emerged two concepts that were then compared. This was done attributing a value to each selection criteria of each concept that reflected its place in the ranking among the totality of the concepts, and
simultaneously to each selection category it was assigned a value that reflects the relative importance of the mentioned criteria in the selection of the vehicle. Table 1 shows results from this procedure.

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</table>

Table 1- Final concept selection

In the winning concept it is directly applied a wheel of an e-bike with a geared motor in the front fork of structure A. All the components used come from the e-bike A7AM20 [13]. The battery is located beneath the rider's seat in or compartment connected to the chassis. A sketch on this concept can be seen in figure 6.

![Figure 6 – Sketch of the winning concept](image)

Project’s Calculations

Forces transmitted by the wind

It is not the focus of this project to study in detail the influence of the choice of the type of sail in the performance of the land yacht. For that reason, it is going to be assumed the vehicle utilizes the type used in reference [10], which is a NACA 0015 wing profile [14]. Having this in mind and that identical wind conditions as in the reference [10] are considered, the same forces are transmitted to the chassis (and for that reason the reactions caused by the wind on the structure under different conditions were directly taken from that work [10]).

Materials and Factor of Safety

For this project were chosen the 304 stainless steel for the fork and 6061-T6 aluminum for all the others structural elements, due to their mechanical characteristics and resistance to corrosion.

Before performing the different analyses, it is necessary to establish the factor of safety for the project:

\[
n = \frac{\sigma_{yield}}{\sigma_{VM}},
\]

which is used to deal with uncertainty in the forces, state of the material and other unknown conditions. There are several ways for determining it, one of the most commons being Pugsley's method [15], which is the one being used in this project. Following this method, it was determined that \(n=2.1\) was an appropriate value for this work.

Static Analysis of the Chassis

Having modeled the chassis and defined the loads it has to withstand, as well as the materials, the next step is to conduct an analysis that allows to determine the deformations and tensions on the structure. For this goal, as well as in all other studies in this document that require a computational approach, it was used the commercial finite elements method (FEM) software Siemens NX. In this section only the chassis is under examination, so the simulation was run
without the wheels or the elements that connect each part (e.g. bolts). The analysis utilizes beam elements to simulate the structure (with the actual tubular cross section), in which each element of the chassis is assumed to the rigidly connected to the ones in its vicinity with every movement constrained in the connection. The main advantage of this approach is the great reduction of the number of elements necessary to be able to achieve acceptable results. Two situations have to be investigated: when the vehicle has all three wheels on the ground (corresponding to normal operation) and the situation where one of the back wheels is hanging in the air with the other two on the floor (a situation that is common in this type of vehicles and for that reason must also be checked). On both cases the forces applied were the weight of the passenger and the previously mentioned reactions of the sail in the structure.

On these analyses was obtained the distribution of stress (figure 7) and displacement along the structure. It was noted that the maximum value of stress in several situations of loading occurred in the region of the weld connecting the central element of the chassis (figure 8).

There were also obtained the values of the forces and moments occurring in critical areas (namely in the bolted joints of the structure).

The analyses had the goal of determining whether the chassis of the vehicle would be submitted, through the course of its expected normal use, to loads or deformations that could endanger the integrity of the vehicle and the safety of the rider. It was possible to verify that this is not the case, since the stresses in all cases studied were below the defined limit (the factor of safety of the project was met in all situations). It was also done an analysis of convergence of the solution, increasing the number of elements in just the curved portion of the tripod (since the straight tubes are correctly represented by few elements, even just one). The results obtained were just slightly different from the previous ones, both in terms of stresses and displacements. This showed that the original analyses had been done with sufficient elements. In figure 9 is showed the mesh used in this refinement.
Vibration Analysis

It was also done a study to determine the natural frequencies of the structure. A plausible way for this type of structure to be subjected to problematic oscillating forces that could cause it to be in a resonating state is when the vehicle moves in an irregular terrain. Since the values of the natural frequencies are greatly influenced by the total mass and the weight of the passenger may vary, analyses were made for different values of this parameter. Keeping in mind the weight of the rider can vary continuously, there is an infinity of values possible for the natural frequencies of the system. However, the range of possible frequencies for each of the modes has its inferior and superior limits in the values for a passenger of 120kg and 50kg (the former is the maximum weight this type of vehicles usually is prepared to withstand and the latter is the minimum weight considered in this work). For the first mode the natural frequencies vary between 1.41 and 1.8 Hz. This is a range in which is conceivable the vehicle could be exposed to vibrations of that magnitude. However, it is still very unlikely this behavior becomes a concern for the structure’s integrity since the exterior loads come from the terrain and a slight deviation from the problematic conditions would rapidly end the issue. Furthermore, it was not considered the damping the wheels provide to the system.

It should be noted, however, that the values obtained for the first natural frequencies were substantially lower than those expected for this situation (which was for them to be around 25Hz). This is therefore a topic that could be address in future experimental works, preferably including the wheels in the system to analyze.

Bolted Joints

There are two types of bolted joints to be studied: the ones connecting the tripod to the tubes that support the rear wheels (there are two of these that are equal) and the one linking the central element to the front wheel connection tube. They can be seen in figure 10.

Considering the data obtained in the static analyses of the chassis, is possible to verify that all bolted joints in the structure are subjected to normal loads and sheer loads, so analyses for both these types of loads are going to be done.

The axial force on the bolts depends on their location due to the existence of bending moments, as illustrated in figure 11.
Figure 11 – Effect of the rotation around the hinge line

To ensure the connection is safe it is only necessary to check the critical bolt, i.e., the one where the loads are the highest. In this situation, to determine which one is the critical, is necessary to consider the geometry of the sections and the directions of the moments applied. Having identified it, to determine the shear load on the bolt are used the following equations ($F_M$ is the shear force cause by the torque, $r_i$ is the distance between bolt $i$ and the hinge line, $Q_i$ the direct shear force applied on the joint and $F_j'$ the force caused by it) [15]:

$$F_M = \frac{M_i r_i}{\sum r_i^2}$$

$$F_j' = \frac{Q_i}{n}$$

In order to obtain the critical load regarding shear was used the parallelogram rule. It was found that in the 4 bolt joint (joint 1) the total force is $F_{s1} = 5337$ N, while on joint 2 (2 bolts) it was $F_{s2} = 2134$ N. The shear stress is given by ($A_s$ is the shear area of the bolt, which is $58mm^2$ for the M10 bolts used):

$$\tau_{sj} = \frac{F_j'}{A_s}$$

The factor of safety is obtained considering [15]:

$$n_{s1} = \frac{S_{xy}}{\tau_{s1}}$$

Regarding the axial loads, equation 2 still applies but in this case $F_M$ is the axial force cause by the bending moment and $r_i$ is the distance between bolt $i$ and the hinge line. In this case, to obtain the total load on bolt is used:

$$F_t = F_M + F_M + F_x$$

To calculate the factor of safety is used:

$$n_b = \frac{A_t S_p - F_i}{F_{ri}}$$

Here $A_t$ is the tensile stress area of the bolt, $C$ is the stiffness constant of the joint and $F_i$ the applied pre-load. $C$ is given by:

$$C = \frac{k_b}{k_b + k_m}$$

In equation (9), $k_b$ is the effective stiffness of the bolt in the clamped zone and $k_m$ the stiffness of the members of the connection in that same zone. These constants are calculated using the following equations [15]:

$$k_b = \frac{A_d A_t E_p}{A_d l_t + A_t l_d}$$

$$k_m = A E_m d e \frac{b d}{l}$$

In the above equations $E_p, E_m$ are the respective Young’s modulus, $A_d$ is the bolt major diameter area, $l_t$ is the length of the unthreaded portion in grip, $l_e$ the length of the threated portion in grip, $l$ the total length, $A$ and $B$ are constants.

It was found that in all joints the factors of safety for axial and shear stresses are met.
**Brakes**

Some models of land yachts have brakes, while in others the decrease of speed is done exclusively using the sail. In this project it is considered that the developed vehicle will necessarily have to include brakes because of the use of the electric motor, namely due to the possibility of using the vehicle without the sail. The first and most obvious choice for this constituent is to use the brakes in the bicycle selected to be used in the winning concept. However, the forces propelling the land yacht (wind and electric motor) are not the same as those that propel the vehicle the brakes originally come from, and for that reason it could not be suited for this application to use the same brakes.

The braking distance, i.e. the distance a vehicle travels between the moment its brakes are activated and the moment it comes to a complete stop, is given by (d is the distance in meters) [16]:

\[ D = \frac{v^2}{2fg} + vt_r \]  

(12)

In this equation \( v \) is the velocity of the vehicle (m/s), \( g \) is the gravitational acceleration (9.81 m/s\(^2\)), \( f \) is the coefficient of friction between the tires and the surface and \( t_r \) (s) is the reaction time of the driver. Substituting the values in equation (12), we have \( d = 33 \text{m} \). The distance may be smaller than the 33m found, since when the sail is being utilized it can also be used as a means of braking.

This is an area in which it would be beneficial to conduct tests in order to determine with more precision whether the selected components are in fact of viable use.

**Electric Circuit**

The constituents that are going to be part of the circuit that are already defined, since they were chosen in the concept selection stage are the following:

- 36V, 500W electric motor (geared hub);
- Lithium ion battery, with 48V and 10Ah (480Wh);
- Controller;
- Throttle (manual/twist).

Besides these, are going to be included other elements in order to contribute to avoid accidents in the electric part of the vehicle:

- Main circuit breaker. The function of this device is to allow a quick disconnection of the batteries from the rest of the components, immediately interrupting the circuit.
- Safety fuse. It interrupts the circuit when an unexpected spike of current occurs due to a short circuit or accident. Normally they are placed in-line with the battery. While the circuit breaker may be manually activated in case the occupant detects an anomaly, the safety fuse does it automatically.

The electric circuit implemented (figure 12) is very simple due to the characteristics of the problem (only a few components are necessary and in a simple configuration). The control is done using a bought controller and for that reason it is presented in the circuit as a black box (it is unnecessary to present the arrangement of its inner components).
Acknowledgements

This work and the academic years that preceded it were only possible due to the help and support of people to whom I must declare my gratitude. I would like to thank first and foremost my supervisor in this thesis, Professor Miguel Matos Neves, for suggesting this challenge and for the constant availability, support and help offered throughout the elaboration of this work. It is also important to recognize the contribution of the different professors and colleagues from whom I have learned in the past few years and thus helped me reach my goals. Finally, I would like to thank my parents are brothers for the support in all these years and in particular in the past months.

References


