Design Issues for Tracked Boat Transporter Vehicles

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Abstract. Elloboat is a tracked vehicle for launching and beaching of small boats and watercrafts, capable of operating in a wide range of operative conditions, here including rescue applications. This paper presents the vehicle architecture and discusses the main design issues. The effects of track dimensions on terrain compaction, bulldozing resistances and, consequently, on track sinkage are analyzed by means of the Bekker model. Obviously, track dimensions also influence the vehicle mass and size, leading to a complex engineering problem. Since vehicle speed and acceleration are limited, stability during locomotion can be assessed using a quasi-static approach, computing the longitudinal and lateral tipping angles for a given vehicle configuration and payload position, and imposing a proper limit to their minimum. Stability analysis can be exploited not only in the design phase, but also for the real-time evaluation of the actual margin of stability, so as to help the operator in the vehicle path/speed planning.

Keywords: Watercraft, Small Boat, Launch, Beaching, Tracked Vehicle, Bekker Theory.

1 Introduction

Today, launching and beaching of watercrafts and small boats are usually carried out using a slide and a winch, if available, or by partially submerging a trailer, sometimes drawn by a road vehicle if the beach is sufficiently accessible. In general, at least two human operators are necessary. Recently, unmanned vehicles for small boats' launching and beaching have appeared on the marked to fulfil the following needs:

- capability of operating also in places not equipped with launching/beaching infrastructures and inaccessible by road vehicles;
- capability of operating also without assistants.

Some of these vehicles can be loaded and unloaded from the top by means of auxiliary devices (for example, the vehicle named Beachlauncher [1]), others are open-bottom and can lift the boat (for example, the so-called Beach Rover [2]). These vehicles can be equipped with either wheels or tracks, although the current trend is to actually employ tracks; for example, the 2018 version of Beachlauncher is tracked, whereas its previous version was wheeled. Actually, these vehicles must travel into the water until the boat floats, so that traction becomes critical, especially on sandy beaches. In such

T. Uhl (ed.), *Advances in Mechanism and Machine Science*,
Mechanisms and Machine Science 73,
https://doi.org/10.1007/978-3-030-20131-9_362

cases, having to deal with unstructured environments and yielding terrains, the preferable robotic locomotion system is by tracks [3-5], due to the large contact surface with the ground. On the other hand, tracks are less energy efficient and slower than wheels, but this is not a critical issue for the present application, where only short distances must be covered (namely, form the storage or the transport vehicle to the shore, and back).

Within this overall scenario, Elloboat represents a practical example of an unmanned tracked vehicle, designed and patented by Ellotech S.r.l. [6], that has been purposely conceived for boats/watercrafts launching and beaching. As previously recalled, design efforts within the present project aim at providing to Elloboat the capability of working in a wide range of conditions (e.g. routine and rescue operations), also in presence of a single operator and without auxiliary devices. In particular, as discussed in [7], tracked vehicles can be classified according to number and layout of tracks. For Elloboat, the simplest scheme has been adopted to limit cost and control complexity: two non-articulated tracks with differential steering. The innovation is related to the special-purpose frame, capable of loading and unloading form a fixed support.

The rest of the paper discusses the main design issues of the Elloboat, and is organized as follows: section 2 describes the Elloboat architecture; section 3 provides an outline of the main design topics; section 4 is focused on the motion resistance of tracks on yielding terrain; section 5 discusses stability during locomotion; section 6 is the conclusion section.

2 The Elloboat architecture

The Elloboat mechanical architecture is composed of two tracked modules (Fig. 1, *a*-*b*) connected to a central saddle with open U shape (Fig. 1, *c*) which carries the boat; the connection between tracked modules and central saddle is not fixed, but realized by means of two independent parallelogram linkages. The parallelogram linkages are actuated by hydraulic pistons (Fig. 1, *h*), the actuators of the tracks being also hydraulic.

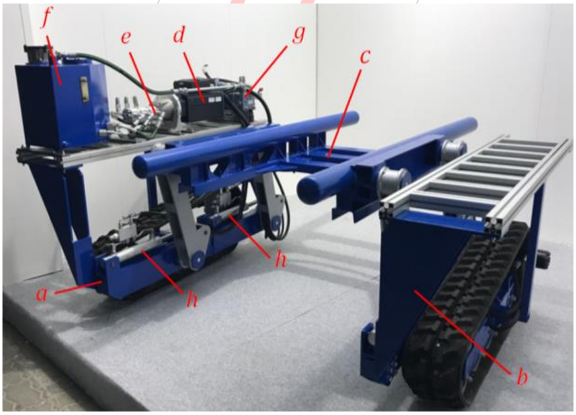

Fig. 1. The Elloboat architecture.

Fig. 2. Elloboat relieving a boat form a fixed support (a) by lifting the saddle.

The primary electric pump engine (Fig. 4, *d*), the pump (Fig. 4, *e*), the oil tank (Fig. 4, *f*) and the remote control electronics (Fig. 4, *g*) are hosted on one tracked module, in raised position to avoid submersion. The prototype of Fig. 1 can carry watercrafts with maximum length of 2 meters, but the realization of larger models is planned.

The vertical displacement of the central saddle is useful for several operations. First, when the boat is placed on a support, the central saddle is lowered, the vehicle is driven under the boat. Then, the boat is lifted by raising up the saddle (Fig. 2) and transported to the shore for launch. This procedure is inverted for placing the boat on the same support after beaching. While travelling on the beach, the saddle can be lowered to improve stability. On the contrary, in case of irregular terrains, the saddle can be lifted to avoid contact with the ground. Finally, the saddle vertical movement is useful during the launching and beaching phases, when Elloboat is partially submerged: the saddle can be lowered to release (launching) or to receive (beaching) the watercraft (Fig. 3).

Fig. 3. The saddle is lowered to release/receive the watercraft during launching/beaching.

3 Outline of the design issues of Elloboat

The mechanical architecture of Elloboat is peculiar in many aspects, and it leads to peculiar design issues. First, there is not a single frame, but the two track modules are joined to the central saddle by two articulated mechanisms, giving rise to an open chain. This open chain, which becomes closed through the contact of the two tracks with the terrain, must be capable of supporting the boat while withstanding the forces arising from track contacts with irregular terrains, that may cause distortion and bending of the vehicle structure.

Each four-bar linkage is a 1-DOF mechanism that, in principle, could be driven by one rotary or linear actuator. Nevertheless, the actuators not only move and support the load, but also have a structural function during locomotion on irregular terrains. Therefore, the choice of the actuation scheme is critical, since it strongly influences the internal reactions between the frame members. The statics of Elloboat is indeed characterized by redundant constraints, and proper hypotheses about track-terrain contacts are necessary to solve it by multibody simulation. These aspects, and the subsequent choice of the actuation scheme with four hydraulic pistons applied to the four cranks of the two parallelograms, are discussed in [8].

In the design of a tracked vehicle, the sizing of the tracks is related to the features of the range of terrains in which the vehicle must operate; this requires the adoption of a proper terramechanics model, as discussed in section 4.

Another important aspect is stability during locomotion, in presence of terrain slopes and obstacles; moreover, stability is influenced by the saddle position, by the position of the boat center of mass with respect to the saddle, and by the boat mass. Stability issues are discussed in section 5.

4 Motion resistance of the tracks

The sizing of tracks (length, width) and of their motors, on the basis of vehicle mass and desired performance, is a fundamental issue in the design of a tracked vehicle. One of the earliest methods to evaluate the behavior of track systems is the Bekker model [4]; in this method, it is assumed that the track, in contact with the terrain, is similar to a rigid footing, and the measured pressure-sinkage relationship allows to estimate the track sinkage and the motion resistance. For a track with uniform contact pressure, the sinkage z_0 is given by:

$$z_0 = \left(\frac{p}{k_c/b + k_\phi} \right)^{1/n} = \left(\frac{W/bl}{k_c/b + k_\phi} \right)^{1/n} \quad (1)$$

where: p is the normal pressure; W is the normal load on the track; b and l are the width and length of the track; k_c, k_ϕ and n are characteristic parameters of the yielding terrain, available in the scientific literature [3]. Using equation (1), it is possible to calculate the work done in compacting the terrain, obtaining the *compaction resistance* R_c:

$$R_c = b\left(\frac{k_c}{b} + k_\phi\right)\frac{z_0^{n+1}}{(n+1)} \tag{2}$$

Another component of motion resistance is the *bulldozing resistance,* due to the presence of yielding terrain R_b in front of the track; it can be calculated as [9]:

$$R_b = b\left(0.67 \cdot c \cdot z_0 \cdot (N'_c - \tan\phi')\cos^2\phi' + 0.5 \cdot z_0^2 \cdot \gamma_s \cdot \left(\frac{2N'_\gamma}{\tan\phi'} + 1\right)\cos^2\phi'\right) \tag{3}$$

where c is the *terrain cohesion* [Pa], γ_s is the terrain specific weight [N/m^3], N'_c and N'_γ are the *Terzaghi's modified bearing capacity factors*, functions of the *internal friction angle* of the terrain ϕ (Fig. 4); moreover: $tan(\phi') = 2/3\, tan(\phi)$.

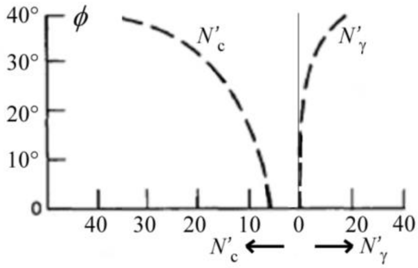

Fig. 4. Terzaghi's modified bearing capacity factors.

The internal friction effects of the track obviously depend on the detailed design of the track itself, and can be assessed with experimental tests or complex mechanical modelling; otherwise, this empirical formula proposed by Bekker can be used for a rough estimation [4]:

$$R_{in} = m(0.222 + 0.0108 \cdot v) \tag{4}$$

where R_{in} is the motion resistance [N] due to the internal friction of the tracks, m is the vehicle mass [kg] and v is the vehicle speed [m/s]. The motion resistance of a single track is therefore:

$$R_t = R_c + R_b + R_{in} \tag{5}$$

Considering also gravity loading, the total motion resistance of the vehicle in presence of a terrain slope α is:

$$R_v = 2R_t + R_g = 2R_t + mg \cdot sen(\alpha) \tag{6}$$

These equations can be used to select the main dimensions of the tracks (b, l) and to estimate the power consumption for locomotion. Obviously, the detailed design of the tracks directly influences R_c and R_b, but also the internal friction resistance R_{in} and the overall vehicle mass m. Consequently, also the gravity resistance R_g is indirectly influenced by b and l. Overall, these mutual relations among vehicle characteristic parameters imply the need for a recursive design approach.

The two resistance components which are directly related to the track dimensions and to the terrain features are R_c and R_b; Figure 5 shows the sinkage z_0 and the sum of R_c and R_b as functions of b and l, for the case study characterized by the parameters collected in Table 1. It is possible to note that, as evident from equation (1), the sinkage decreases when b and l increase, and consequently also the terrain resistance decreases; the sensitivity to l is higher than the sensitivity to b. On the other hand, large tracks can be not acceptable for the overall vehicle dimensions, and increase the vehicle mass (directly proportional to R_g). Therefore, it is necessary to find a proper design trade-off.

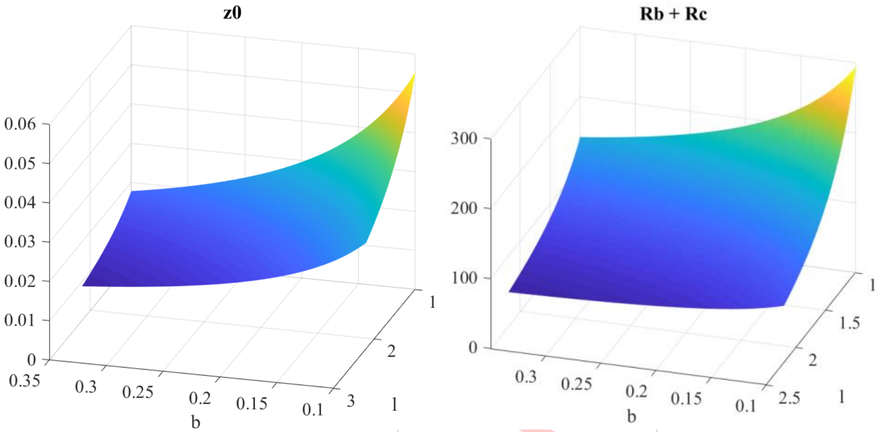

Fig. 5. Track sinkage (z_0, left [m]) and sum of compaction and bulldozing resistances (R_b+R_c, right [N]) as function of the track width b [m] and length l [m].

Table 1. Main vehicle and terrain parameters (dry sand).

Vehicle mass with payload		1300 kg	
Terrain type		Dry sand	
k_c	0,99 kN/m^{n+1}	n	1,1
k_ϕ	1528,4 kN/m^{n+2}	N'_c	16,5
c	1.04 kPa	N'_γ	5
ϕ	28°	γ_s	17800 N/m^3

5 Stability during locomotion

Another important design issue is the stability of the vehicle during locomotion. Since the speed and the acceleration of this type of vehicles are low, it is reasonable to resort to a quasi-static approach. The *tipping angle* is defined, according to the standard ISO 4305-2014, as the rotation around the pivot edge necessary to vertically align the center of mass to the pivot edge, reaching the limit of stability. Since dynamic effects are not explicitly taken into account, a minimum non-null tipping angle is imposed to define the range of possible operative conditions, in terms of maximum pitch (α) and roll (β) caused by terrain slope and/or obstacles.

The position of the overall center of mass is not fixed, but is function of:

- position of the saddle: the four-bar mechanisms change the longitudinal and vertical coordinates of the saddle with respect to the tracks;
- position of the boat center of mass with respect to the saddle;
- boat mass.

Keeping constant the position of the saddle and the boat center of mass, a higher boat mass moves upward the overall center of mass G_{tot}, reducing the longitudinal tipping angle φ_1 and the lateral tipping angle φ_2 (Fig. 6).

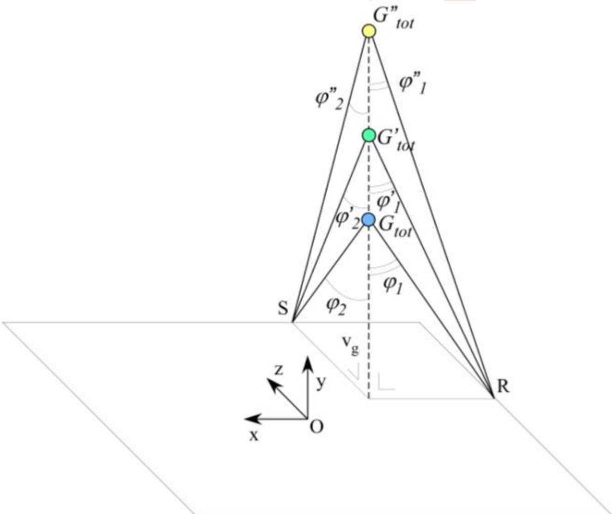

Fig. 6. Longitudinal and lateral tipping angles φ_1 and φ_2 as functions of the boat mass: G_{tot}, G'_{tot} and G''_{tot} are different positions of the overall center of mass corresponding to increasing boat masses.

For both tipping angles, there are two possible pivot edges, so that it is necessary to select the minimum for any configuration. The tipping angles vary in presence of pitch and roll due to the terrain configuration (Fig. 7).

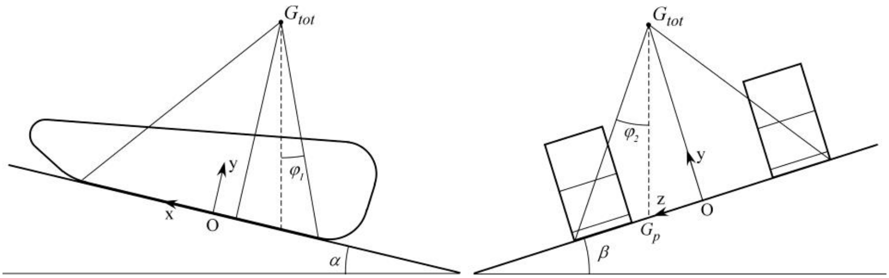

Fig. 7. Reduction of the tipping angles in case of pitch (left) and roll (right).

For any admissible position of the overall center of mass with respect to the track coordinate system (O(x,y,z), Fig. 7), the lateral and longitudinal tipping are calculated as functions of α and β, and the possible range of operative conditions can be defined imposing a minimum value φ_{lim} to $\varphi_{\text{min}} = \min(\varphi_1, \varphi_2)$. Figure 8 (left) shows the 3D surface representing φ_{min} as a function of α and β for a given vehicle configuration; this surface is the minimum of the two surfaces φ_1 and φ_2, whose level curves are represented in Fig. 8 (right).

The admissible operative range corresponding to the vehicle configuration can be defined intersecting the surface φ_{min} with a horizontal plane $\varphi = \varphi_{\text{lim}}$.

For lower φ_{lim}, the operative range is higher, but the margin of stability is lower. A proper margin of stability at the maximum vehicle speed with payload (0.5 m/s) is $\varphi_{\text{lim}} = 10°$; to face higher slopes, a lower margin of stability can be accepted (5°), but significantly reducing the vehicle maximum speed (0.05 m/s). Installing an inclinometer on the vehicle, φ_{min} can be calculated in real-time, to suggest to the operator when to reduce the speed or to modify the path, in order to avoid excessive slopes.

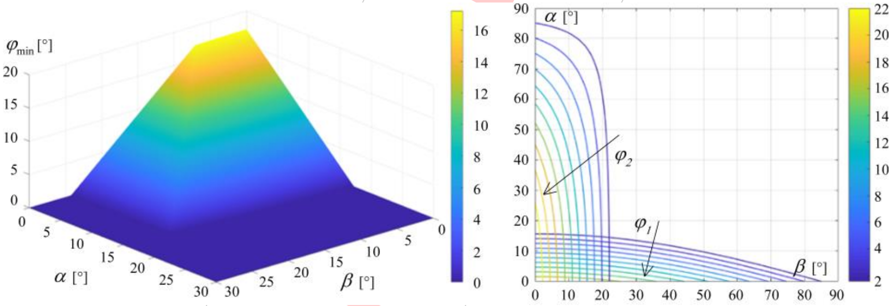

Fig. 8. Stability margin φ_{min} as a function of α and β.

6 Conclusion

The tracked vehicle Elloboat has a peculiar mechanical architecture, based on a central saddle, carrying the payload, connected to two track modules by means of four-bar mechanisms. All hydraulic actuators and their auxiliary devices are located on the track modules, therefore the central saddle is relatively lightweight, but its structural behavior is quite complex: the mechanical architecture is redundantly constrained, and the internal reactions are strongly influenced by the actuation layout and by the contact condition with the terrain [8].

Another important design issue is the sizing of the tracks, discussed in section 4. The Bekker model [4] can be used to evaluate the track sinkage and the compaction and bulldozing resistances as functions of the track dimensions for a given yielding terrain. Larger tracks reduce both sinkage and terrain motion resistance, but increase the resistance due to internal track friction, and the mass and encumbrances of the vehicle. Therefore, track sizing is a complex engineering problem, related also to the availability of off-the-shelf components, and almost impossible to optimize numerically.

Also stability during locomotion must be carefully taken into account in the design phase. The stability margin can be evaluated considering the minimum tipping angle of the vehicle φ_{min}, and imposing a minimum limit value φ_{lim} to φ_{min}. The minimum tipping angle, for a given vehicle configuration (saddle position, position of the boat on the saddle, boat mass) depends on the terrain configuration, which determines the pitch and roll angles. In particular, stability analysis turns useful not only in the design phase. In fact, if the vehicle is equipped with an inclinometer, φ_{min} can be calculated in real-time on the basis of the vehicle configuration, providing useful information on how to regulate the speed and how to safely choose a proper vehicle path.

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