Investigation into the steering ability problems of compact hovercraft.

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ABSTRACT: The present paper investigates the requirements and the turning ability problems of the hovercrafts characterized by compact dimensions (with small width, powerful engine and big propellers). These vehicles require a very accurate control system, to combine the command of turning or trim with the possibility of reversing the thrust. In this article we briefly describe compact hovercrafts and focus on the various systems projected to improve their turning ability. We give an account of the steps which led to achieve our technical solutions and show the various systems of passive control surfaces adopted: to verify the different assessed implementations, several on-field tests have been performed on two vehicles, the *Hover4* and the *Multipurpose Air Cushion Platform (MACP)*. Finally we illustrate the ultimate chosen version of the system, in particular we outline the positive effects of the adoption of an unusual axis of rotation used to solve the problems created by the vertical rudders, whose centre is higher than the barycentre of the vehicle.

1 INTRODUCTION

The topic treated in this article is related the development of a new compact professional hovercraft named ”MACP” (Multipurpose Air Cushion Platform).
Hovercrafts, also known as air cushion vehicles (ACV), are amphibious vehicles able to operate both in speed and in stationary conditions on land, water, mud, ice and other surfaces. They work by creating a cushion of air, at low pressure and high flow rate, between the hull of the vehicle and the underlying surface. This cushion is contained beneath the hull by a set of peripheral skirts granting the lift of the craft at the required height.
This paper deals with the turning problems of a special class of Air Cushion Vehicles named ”Compact hovercrafts”.
The results reported in this paper, generally applicable to this class of vehicles, come from tests on the prototype of “MACP”. The latter vehicle arises from the 7thFP project named Hoverspill and aimed to create a new professional, powerful (MACP powered by a 130kW diesel engine), lightweight and easy-transportable hovercraft for rapid response in oil spill emergency situations. MACP is characterized by diesel engine, compact size, wide cargo space and modularity which provide several utilizations, both for research development and for working purposes (e.g. oil Spill, bathymetric surveys, search and rescue). A hovercraft is defined *compact* (figure 1) if its dimensions are limited to allow the transport on a trailer without the mark “special transport”: $2.50\,m$ in width and a maximum length of $7.50\,m$ (ideally between $5.0\,m$ and $7.0\,m$). These vehicles have a high potential: they are light and fast and can operate in presence of strong currents, shallow water and protruding obstacles. Even so, early they did not have

Figure 1: MACP, a *compact* Hovercraft

the expected success after they were conceived in the $60'$. Certainly there are several implementation problems: ACVs require a design which takes in consideration the need of low weight, the instabilities cre-

ated by the presence of the air-cushion and the environmental constrains like wind and waves. In addition, the existing work-boats rules, which impose the possibility of the reverse thrust and the use of low-flammable fuel (e.g. diesel and kerosene), could be applied to large ACVs, but where impracticable for compact ones; only the recent creation of lightweight diesel engines allowed the development of a new research respecting these rules. MACP is the first vehicle responding to all these requirements
The project of a compact hovercraft equipped with diesel engine, high efficiency propellers, separate lift system and reverse thrust, requires to solve many problems: one of the main is the realization of proper turning devices.
The implementation have to mediate among conflicting requirements: the small width is good for terrestrial performance, but limits the stability skills , the use of very high power and big propellers requires a good and safe turning management.
Hovercraft's manoeuvrability is very different from that of boat's and car's. Wheels in cars, hull and rudders on boats are elements of directional friction producing a large centripetal force which allow curves or braking. In a hovercraft the almost complete separation from the underlying surface reduces to zero the directional friction and the craft slips considerably, unless special measures are taken by forcedly deviating propeller air flows.
All these features influenced our design of the steering devices.
Some hovercraft of small dimensions are equipped with a thrust reverser system of new conception (www.neoterichovercraft.com), which allows a more efficient manoeuvrability, even in confined spaces. But this system is hardly applicable to compact vehicles characterized by high diameter propellers and separate lifting system.
We investigated and tested various configurations, which led to the evolution reported in this document. These were systems of passive control surfaces, studied to improve and simplify the controllability of the vehicle in terms of turning ability and reverse thrust
Finally we found a new answer, the *Flaptons system* (www.softhull.com/unikflapton.html), which, in addition to the above required performances, allows the complete control of the vehicle in terms of stability, trim and turning. It automatically maintains the vehicle parallel to the underlying surface, even in the turns at maximum power.

2 DESIGN OF A REVERSE SYSTEM

According to the aim of the MACP project, a Compact Professional Hovercraft is intended to satisfy the following characteristics:

- Big diameter propeller, with high thrust and good efficiency.
- Separate thrust and lift system for good management of the different operational needs: the air necessary for the cushion is provided by ad-hoc fans, while on smaller vehicles the air for the lift is obtained by partialization of the air flow produced by the main propeller.
- Diesel Engine: in compliance with work-boat rules. vertical rudder
- Capability of reversing the thrust, reacting quickly to commands and *Safely returning to port* after serious breakdown.

High efficiency propellers must have a huge diameter: $1.3 \div 1.5\,m$ and their utilization is fundamental for vehicles that need to work in harsh environments and in adverse situations, when the need of a power surplus is necessary for a safe return to the base.
The design of a reverse thrust system has to take this parameter into consideration.
An in-depth survey on the argument shows that many thrust reverser systems have been adopted on different vehicles, we list them:

1. Acting on the propeller:
   - Variable pitch propeller (with possibility of negative pitch).
     It is a solution adopted on great hovercraft which have a different operative logic, big inertia and a limited power to weight ratio.
   - Reversing of main propeller rotation.
     This solution cannot be adopted for its slowness of actuation: the reverse system is a safety system and requires promptness of response.
2. Flow reverser surfaces:
   - Neoteric Reverse System (figure 2).
     Constituted by two shells, one per-side permits a good manoeuvrability not only for braking. Currently it is the most efficient system. It requires lift system integrated in the main propeller. It is adopted for small diameter propellers.
   - Aeronautical reversers (figure 3).
     These have the advantage of being completely hidden when not used.

Figure 2: Neoteric Reverse Cups

We performed a comparative analysis of the different reverser systems previously described.
The choice of a *variable pitch propeller* causes slowness and a bigger regulation complexity, further it requires a routine of specialized maintenance. In the course of reverse motion this is an efficiency system, but doesn't give the possibility of controlling the direction. Hence it is not suitable for a hovercraft working in harsh zones.
The *aeronautical system* is thought for the very high speeds of jets and is hardly efficient in the case of an hovercraft.
On the other hand the system developed by *Neoteric Inc.* (and afterwards adopted by different manufacturers) is successfully utilized for its ease of run and for its efficiency . This system has the important feature of a non-symmetric actuation of the two shells which gives the possibility of curving with strict curvature radius. Nevertheless, in order to keep the cups efficiency, the thrust propeller diameter has been strongly reduced. Since this solution causes the impossibility to use a $1.3\,m$-diameter propeller, it cannot guarantee appropriate performances for working in a sea environment.

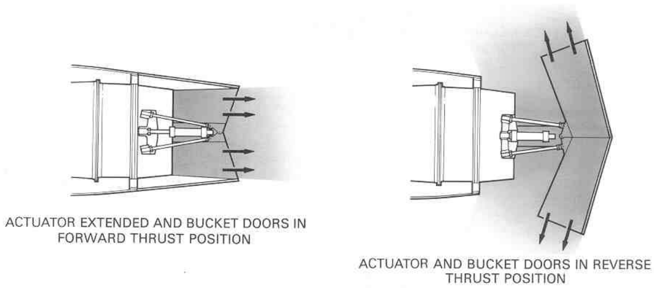

Figure 3: Aeronautical thrust reverser

3 SHELL THRUST REVERSER SYSTEM

A natural approach to design the reverse system, was to adopt an almost Neoteric geometry, but using the typical shape of the Pelton turbine blade; this is adaptable to the $1.3\,m$ and can be combined with the rudders used for normal turning operations. Hence we focused on the realization of a device formed by two shells, one per side.

3.1 *The design*

Figure 4 represents the design and a schematic section of the reverse shells. These can be actuated when needed while small vertical rudders provide for the turning operations. The shells are extended by ducts. The dimensional constrains confirmed the possibility of using these shells for the flow inversion.

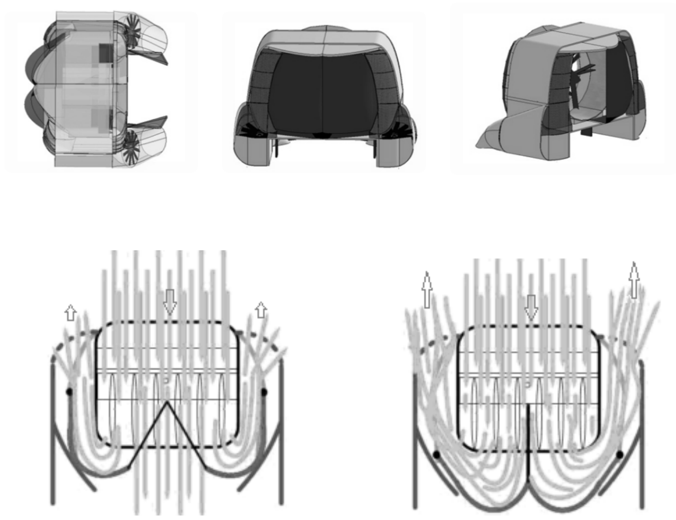

Figure 4: Design of Shell Thrust Reversers

3.2 *Tests and results*

The prototype of this system was realized and tested on the hovercraft *Hover4* of *SOA Srl* company, a small hovercraft ($4.3\,m \times 2.0\,m$) with a lift system integrated in the propulsion.
The elements necessary to brake and reverse the motion needed various adjustments, since the shells must rotate at different angles without interference with the external duct and their geometry is complex.
The first problem, already hypothesized at the design stage, is the generation of vorticity at the entrance of the return conduit. In agreement with the simulations it was evident that a swirling motion is established between the outer wall of the Venturi duct and the inner wall of the backward duct. This is due to dimensional limitations.
Dimensional constraints brought to a *flattening* of the roundness of the shells; for this purpose it was recorded a stagnation point in the centre of the shells reducing to low values the amount of reversed flow, with an appreciable loss in efficiency. It was clear that the air flow at the exit of the duct was not relevant for the purposes of a push reversed.
Another negative result was assessed while testing the rudders (positioned immediately downstream of the propeller). These did not give the desired effect, due to the presence of the return conduit receiving the flow deviated by the rudders (figure 5) thus reducing the manoeuvrability. No way was found for solving the two problems without increasing considerably the

size of the whole system. One has to consider that the lack of friction with the ground makes the hovercraft prone to lateral winds, hence any increase in transversal area must be avoided.

Figure 5: Hover4 and flow on the return conduit

4 RUDDER-REVERSER SYSTEM

Now we describe our second approach to solve both the reverse thrust problem and the rudders interference with reversers.
The implemented configuration is the so called Rudder-Reverser System (RRS): it involves the use of 4 movable profiles and 2 fixed reversers.

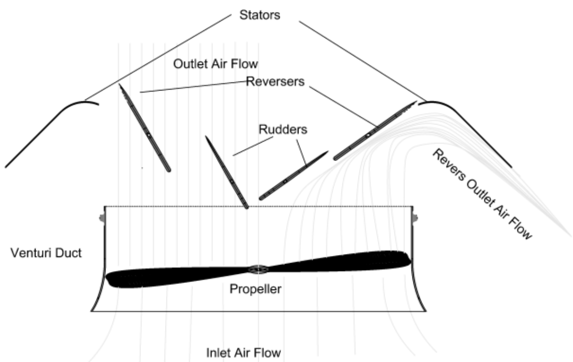

Figure 6: RRS in a transversal section

4.1 *The design*

RRS was implemented looking for a preliminary design and some configurations performance by means of a lumped parameter model.
As shown in figure 6, the RRS is a system of passive control surfaces which uses the flow produced by the propeller to steer the vehicle. These surfaces are constituted by 4 vertical profiles and 2 stators. We call *rudders* the central control surfaces and *reversers*, the lateral ones: they work in pairs (2 per side) as normal rudders, but when actuated to their maximum angle, form a unique surface that accompanies the flow to the *stators*. These latter, one on each side, are fixed elements shaped as the surfaces of the *Shell thrust reverser* and allows the reverse of the thrust.
The system is driven by an ad-hoc-studied element (*UNIK*) that permits both the simultaneous or differential actuation of the left and right RR.

4.2 *Tests on Hover4*

RRS was tested on the *Hover4* vehicle (figure 7)

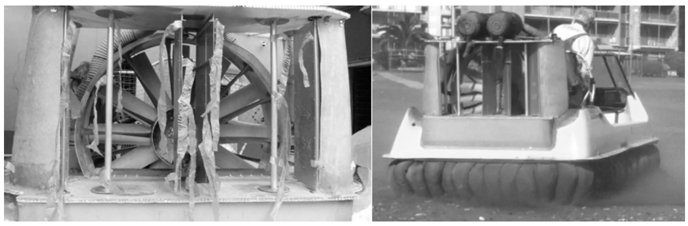

Figure 7: RRS on *Hover*4

Tests performed with the use of anemometers allowed to assess qualitatively the velocity profile at the trailing edge of the reverser. The reverse thrust was 20% of the forward and permitted a low speed reverse motion and a sudden crash stop. The main issue with this model is that the *Hover4* has only one propeller for both lift and thrust. The system was therefore intended to accomplish the lumped parameter calculations. A second version was mounted and tested on the MACP.

4.3 *Tests on MACP*

The good results of the experiments on *Hover4* suggested to apply RRS on the MACP. But, when the system was activated on MACP we discovered that the turning ability of the vehicle was inefficient; in fact the tests at sea demonstrated a tendency of the craft to incline towards the outer side of the curve.
However the awareness of this issue led to the understanding of a peculiar problem of compact hovercraft, we discuss it in next section.

Figure 8: RRS on MACP: attempted left turn

Table 1: Dimensions of Rudders on Bigger Hovercrafts (Yun and Bliault)

Craft identification	SR.N5	SR.N6	711-IID
Length$[m]$	11.8	14.6	15.6
Beam$[m]$	6.6	6.6	6.8
Rudders number	2+2	2+2	2+2
Rudders Total Area $[m^2]$	2.2	2.2	3.96

5 THE PROBLEM OF VERTICAL RUDDERS

To project an adequate steering system for professional and compact marine hovercraft, as described in section 1, we must fulfil different features which create serious problems. The necessity of realizing the reverse thrust, combined with the presence of a big diameter propeller, impose to utilize rudders with a wide surface. Hence to cover completely the air flowing from the propeller disc, we need at least $1.5 \div 2\,m^2$ of rudder area. We report in table 1 the rudders dimensions compared to the hovercraft dimensions of well known ACVs: these areas are comparable to the area needed for the RRS, but the vehicle dimensions are much greater then those of compact hovercraft. Therefore, for what concerns the steering, the ratio (RRS area/Cushion area) is over-abundant. This fact amplifies the problem of vertical rudders.

In fact a vertical rudder, which has the centre of pressure in high position over the centre of gravity, not only creates turning moments, but also a drifting force and a rolling moment, which give rise to an outward banked turn. Thus when the ACV is turning by means of an air rudder, also yawing, heeling and drifting will occur simultaneously.
In more detail, vertical rudders create two main effects: one is the required steering the other is a negative component that tends to push down the side of the hovercraft on the external part of the curve. Namely, on steering, the craft is subject to three negative effects (figure 9):

- the vehicle leans on the outer side and wets the skirts on that side, increasing the resistance: this produces a negative steering moment.

- As a consequence, the air cushion tends to shift to the inner side of the craft, and so the resulting pressure pushes the vehicle on the external side creating a drifting effect.

- The bow of the vehicle descends and *wets* causing the deceleration of the vehicle.

When ACV is heeling, the centre of the cushion area will shift to the side which is sinking to offer a restoring moment. In compact hovercraft this component is imperceptible, due to the small width of the hull. Therefore we have no natural restoring moment from the cushion; a significant stability moment can only be produced by the deformation of peripheral skirts. This problem may be a deterrent to the use of

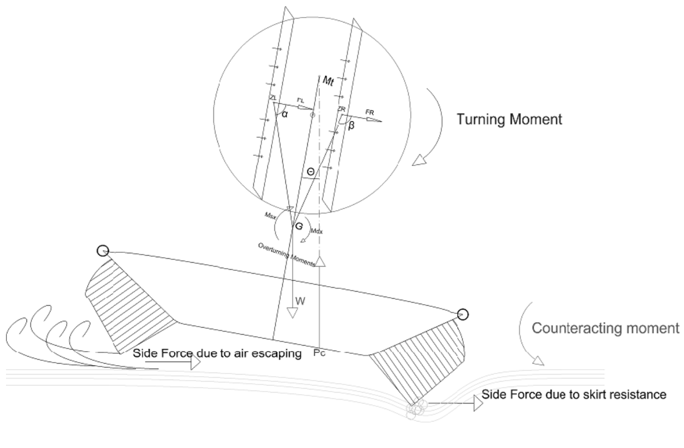

Figure 9: Turning with vertical rudders

powerful and compact marine vehicles. Various solutions have been found to solve stability while turning: some hovercraft use a combination of horizontal flaps and vertical rudders, other vehicles use small inclined rudders (thus decreasing the negative component), whose centre is in the lower part of propeller's disk; other vehicles use actuated separately Elevons (Longley 1999). But the above mentioned solutions are hardly applicable for ACVs which provide the reverse thrust. In the next section we illustrate our answer to these issues.

6 TRANSVERSE REVERSERS

To solve the problem of inclining moment combined with the need of reverse thrust a new system was studied.

6.1 *The design*

The system is formed by several control surfaces (Flaps) positioned downstream of the propeller. The flaps are positioned symmetrically on both sides and can be actuated separately.
The innovation stands in the fact that these flaps have horizontal rotation axis, but every left flap and the corresponding right one form a suitable angle ($\pm 120^0$) as shown in figure 10.

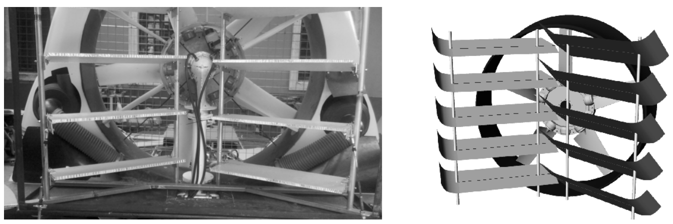

Figure 10: Flaps inclined along the vertical axis

With this solution, every flap form a suitable angle with the flow induced by the propeller: When actuated (separately) they create a force that can be subdivided into three components:

- one horizontal component creates resistance and a turning moment,

- one transversal force creates both a turning moment about the vertical axis and a undesired inclining moment about the longitudinal axis,
- One vertical force acts downwards and opposes to the wrong one given by the transversal component.

The resulting moment about the longitudinal axis (function of the actuation angle of the flaps) is positive up to a certain angle (in our case $\leq 45^0$). It equilibrates the ACV during turning, more precisely we obtain:

- positive lateral thrust due to the air cushion,
- trimming moment that upwards the bow of the vehicle,
- correct turning moment in case of wetting of the skirts in the internal side of the curve.

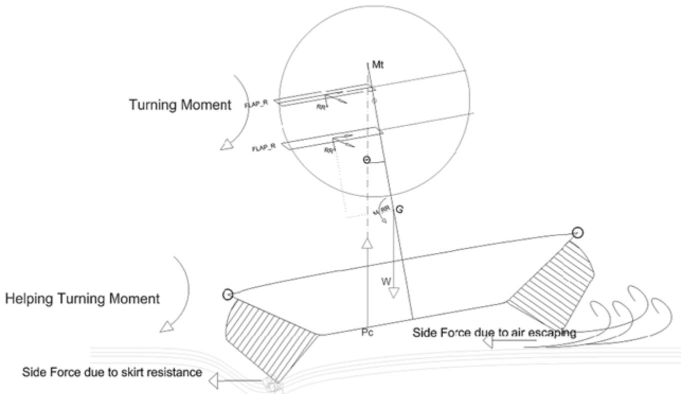

Figure 11: Turning with Transverse Reversers

When totally actuated, the whole flaps create a surface that in the horizontal plane accompanies the external side (figure 12): the flaps are shaped in the way that the extreme outer part of the flaps is curve and permits the flow reversion.

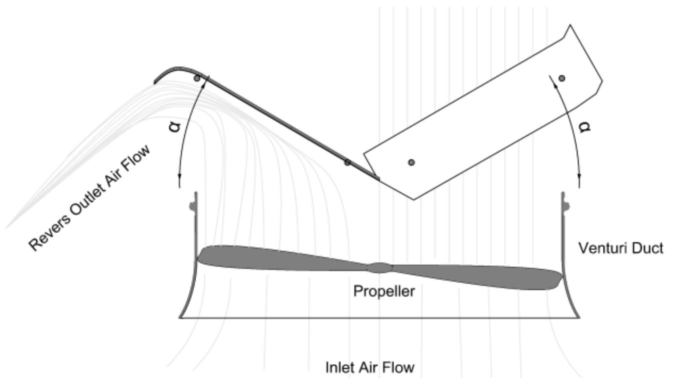

Figure 12: Flap totally actuated reverses the thrust

6.2 *Results achieved*

The adopted solution gave positive results during the tests, in particular to what concerns the turning diameter and the ability to compensate the adverse inclining moment.
Moreover the presence of horizontal surfaces gives the possibility of controlling the longitudinal trim of the vehicle: this can be done by actuating simultaneously the right and left flaps.
The adoption of a system using trim control gives considerable advantages:

- the longitudinal trim can be finely modified when in straight motion
- the possibility of a positive trim (stern up) increases the ability of the hovercraft in standing start

However, the tests outlined the limitation of this system: to realize a curve one has to actuate one side per time (the one in the inner part of the curve) because the contemporary actuation of the two system (e.g. right up and left down) creates opposite turning moments. This obstacle is solved by the introduction of the *Flaptons System* which adopts an unusual axis of rotation.

7 FLAPTONS

The design of the Flaptons is a real innovation in terms of control surfaces.
This solution, by the adoption of an unusual axis of rotation, gives qualitatively the same results as the previous one (positive inclining moment, trim control, reverse thrust) but also the quantitative improvement of the turning behaviour of the ACV.
With this system the contemporary actuation of the two sides gives positive effect to the turning ability. To realize a curve the Flaptons are rotated about

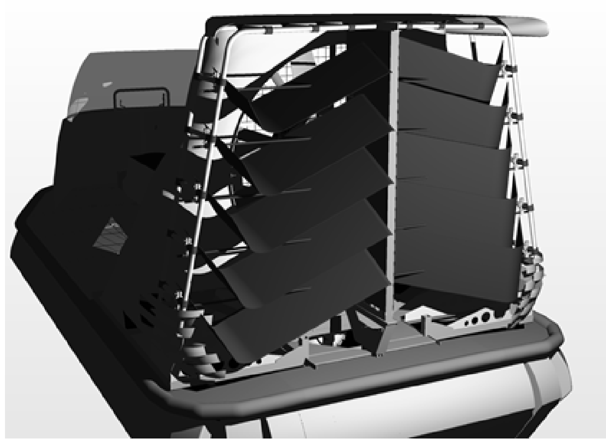

Figure 13: The Flaptons system

their axis of rotation in the following way: the trailing edges of the Flatpons in the internal side of the

desired curve are moved upwards while those of the opposite Flaptons are moved downwards. Both create a steering component that has positive effect on the steering moment.
The geometry of the systems can be calibrated in function of the distance between the centre of pressure of the global system and the barycentre of the hovercraft.
A detailed description of the Flaptons will be the object of future studies, after the necessary testing phase in progress.
In figure 14 it can be appreciated the correct moment, inclining the hovercraft in the internal side of the curve.

Figure 14: Turning Tests with Flaptons

8 CONCLUSIONS

In the last years the increasing need of compact professional hovercraft was not covered by the development of ad-hoc vehicles adapt for working in harsh ambients. One of the main problems encountered by the designers is the contemporary requirement of high efficiency propellers, road transportability and reverse thrust.

The MACP project intended to fulfil all these needs, dealing with the hard difficulties that were encountered in the matching of these features, in particular the design of a steering and thrust reversing system.
In this paper we explained the steps and needs which led to the invention of the *Flaptons*, our solution to the steering and thrust reversing problem for a compact hovercraft.

We first considered several different solutions and described the results of the implemented tests.

The use of reversing-shells proved to be not efficient due to the need of big elements that cannot answer to the need of promptness of response, good controllability and mismatching with the compact dimensions.

The use of vertical rudders used also as reversing system in the configuration *Rudder and Reverser System* can be effective on smaller vehicles but is not adapt to compact professional ACVs, due to the huge surface necessary to completely reverse the flow produced by the propeller. This creates an unwanted component that inclines the vehicle in the external side of the curve resulting in several negative effects.

On the contrary Flaptons system uses a particular geometry and an unusual axis of rotation, not lining on the surface. The adoption of this technique solved all the problems encountered by the previously studied systems. It is now mounted on the MACP vehicle and subjected to patenting phase.

In conclusion this paper gives the guidelines for projecting the steering system of a compact hovercraft. Future projects may use these advices to create vehicles that can open the market of compact hovercraft.

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