An autonomous Hovercraft with Minimum Energy Consumption

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***Abstract*—The objective of this work is to introduce an autonomous Hovercraft with minimum Energy consumption. To achieve this goal, a computer simulation in addition to practical testing of a simple hovercraft model have been carried out. A mathematical model for the hovercraft is considered and simulated in the MATLAB/SIMULINK environment. A navigation system with Global Positioning System (GPS) integrated with an Inertial Measurement Unit (IMU) sensors are used to monitor the speed, position, and the direction of the hovercraft for the autonomous operation. Two motors with propellers are used for the lifting and thrust systems, while a third one is used for the rudder movement that controls the direction. Specific resistance (Ɛ) index is used to test the hovercraft performance. The results of the practical experiments of moving the hovercraft between two and three points are compared with that of the computer simulation. The distance error from the actual target has been found to be in the range of about 18%, which proves the idea. It should be noted that this significant error is due to the fact that the GPS considered is a low price commercial one and using more accurate one will result in more satisfactory results. Based on the computer simulation and practical testing results, a look up table has been prepared to help in deriving an algorithm for controlling the RPM of lifting and thrust Fans based on the minimum optimum specific resistance**

Keywords—component; Hovercraft; Navigation; Dynamic Modeling; GPS; IMU; PID; Specific Resistance.

I. INTRODUCTION

An autonomous hovercraft with three actuator inputs controlled by a microcontroller with the necessary information from a GPS and an IMU sensors has been designed, implemented, and tested. The considered hovercraft comprises two fans (propellers): One is used to inflate the "skirt" under the vehicle, while the other provides the thrust force. The inflating propeller is responsible for lifting the hovercraft by forcing air (increasing pressure) under the hovercraft causing it to raise above the surface. Also high air pressure inside the cushion enables the hovercraft to float and move smoothly on different land surfaces. The other propeller provides thrust force, as the air leaves the fan and directed by the rudder enabling the hovercraft to go straight or to turn as required. Fig. 1 shows a schematic of this hovercraft.

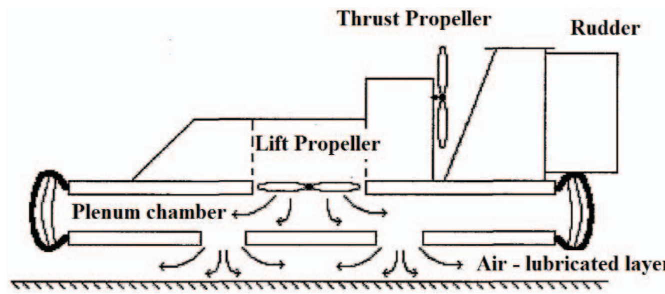

Fig. 1. Schematic of a hovercraft [1]

The previous studies conducted by several researchers focus on different types of hovercraft ranging from the human driven hovercraft to the remotely controlled ones.

Some of these researchers focus on the dynamical modeling [1, 2, 3, 4, 5]. Others consider testing the stability and controllability of the systems [6, 3, 5, 7].

Proportional Integral Derivative (PID) controller is selected to control the hovercraft [6, 2].

Design and development of a hovercraft prototype with full basic functions using two or four fans are considered in [6, 8, 9]. Remote control via wireless (R/C) for the position tracking has been used by [10, 3, 4].

Recently, autonomous hovercraft is studied with a navigation system for its trajectory control [1, 10].

In reference [11], the specific resistance has been determined and reported for various transportation means but not including the hovercraft vehicles.

In this work, a computer simulation in addition to practical testing of a simple hovercraft model have been carried out. In order to study the specific resistance of the hovercraft vehicles; different combinations of thrust and lifting forces are considered and the corresponding specific resistances are determined and reported. This may help in designing an optimum control system for speeds of both thrust and lift fans of the hovercraft based on minimum energy consumption.

II. PROPOSED HOVERCRAFT

A. Mechanical System

Referring to Figure. 2 and Fig. 3, a small model of the hovercraft with two brushless motors integrated with two

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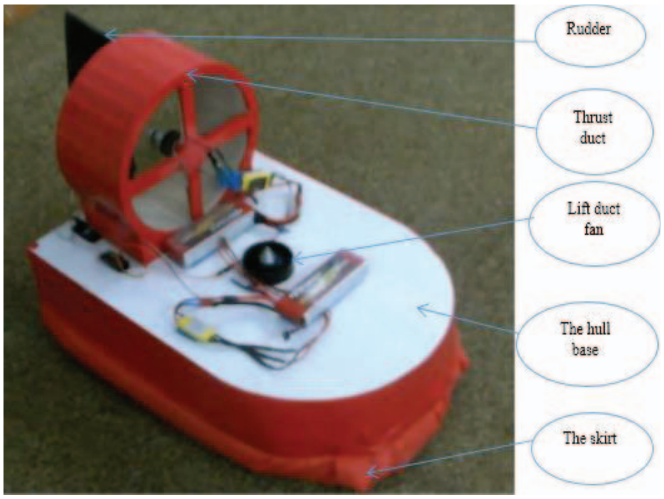

Fig. 2.The proposed hover craft

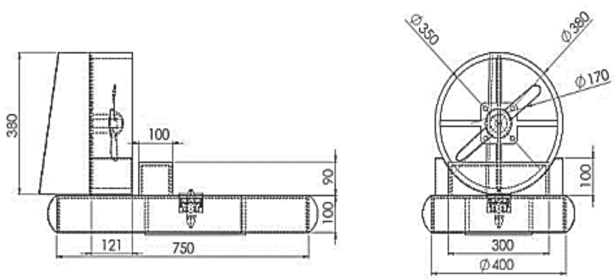

Fig. 3. The hovercraft main dimensions.
(All dimensions are in mm)

propellers is used. One is for the thrust force and the other is for the lifting force.

An electronic control system for a remotely & a completely autonomous vehicle has been designed and built. A servo motor with a rudder is used for the steering control.

B. *Control Board and Sensors*

An Ardu Pilot Mega (APM) 2.5 board is used as the main controller for the hovercraft with an IMU sensor built in it and a GPS sensor are being considered as part of the designed control system. A radio telemetry 915 MHz wireless module is being used with the board for wireless connection with the monitoring computer.

A Radio Controlled (RC) remote control is used for the manual remote control. Two Electronic Speed Controllers (ESC) are used for the speed control of the thrust motor and the lift motor using PWM technique.

III. Mathematical modeling

Referring to Fig. 4, the hovercraft has one thrust fan with a rudder to direct the air according to the steering signal from the control unit. The thrust fan force (F_x) with the rudder angle (δ) provide the inputs for the system.

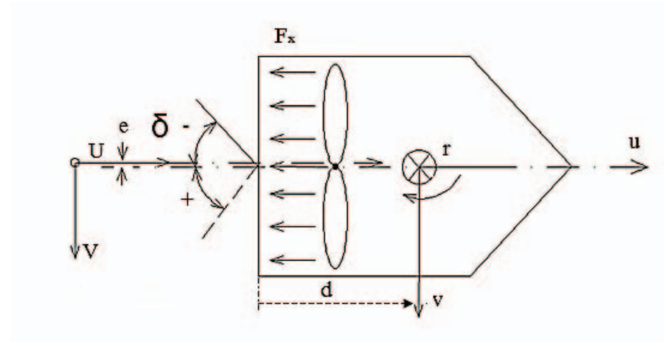

Fig. 4. The Hovercraft thrust and direction inputs

Governing equations:

Referring to Fig. 4 and Considering Newton's second law, the following equations can be arrived at:

<u>In the X direction:</u>

$$\dot{u} = \frac{F_x\ (1 + \mathrm{Cos}(\delta))}{2m} - \frac{b_x\, u}{m} + \omega\, v - \mu_1 \frac{2}{\pi}\ (mg - F_l)\ \arctan(5000\, u) \tag{1}$$

<u>In the Y direction:</u>

$$\dot{v} = \frac{F_x\ \sin(\delta)}{2m} - \frac{b_y\, v}{m} - u\omega - \mu_2 \frac{2}{\pi}\ (mg - F_l)\arctan(5000\, v) \tag{2}$$

<u>In the Yaw direction (Rotation about Z axis):</u>

$$\dot{\omega} = \frac{F_x\, d\ \mathrm{Sin}(\delta)}{2I} - \frac{b_\theta\, \omega}{I} - \mu_3 \frac{2e}{\pi}\ (mg - F_l)\ \arctan(5000\, \omega) \tag{3}$$

Where;

b_x… is the translational viscous coefficient of friction in X direction (kg/s),

b_y… is the translational viscous coefficient of friction in Y direction (kg/s),

b_θ … is Rotational viscous coefficient of friction (kg m^2/sec),

d ….. is the distance between the center of gravity of the hovercraft and the point where the rudder is attached (m),

e … is the difference between geometric axis and principle inertia axis (approximately equals to 0.001 m),

F_l ….. is the lifting force (N),

F_x ….. is the thrust force (N),

g ….. is the gravitational acceleration (9.81 m/s^2),

I….. is the Moment of inertia of the hovercraft around the vertical axis (kg m^2),

m ….. is the Mass of the hovercraft (Kg),

μ_1 , μ_2 and μ_3 ….. are the Friction coefficients in u & v directions; respectively, and

δ….. is the rudder angle (rad).

IV. CONTROLLER DESIGN

PID controller is used as a controlling method in both simulation and experimental tests considered in this work.

A. Linearization :

For linearization, the following are assumed:

- The tangent plane (North, East, Down) is taken as the local navigation frame.
- The tangent frame is obtained by attaching a plane to the surface of the Earth at a specific point.
- Coriolis acceleration is neglected considering small speeds.
- There is no contact with the ground and accordingly, the coulomb friction will be zero as maximum lift force is assumed.
- $F1=\frac{F_x}{2}(1+\cos(\delta))$ and $F2=\frac{F_x}{2}\sin(\delta)$

B. State-space model:

Accordingly; the linearized dynamic equations of the hovercraft system in state-space form are written as follows:

$$\begin{bmatrix}\dot{\delta u}\\ \dot{\delta v}\\ \dot{\delta \omega}\end{bmatrix}=\begin{bmatrix}-b/m & 0 & 0\\ 0 & -b/m & 0\\ 0 & 0 & -b_\theta/I\end{bmatrix}\begin{bmatrix}\delta u\\ \delta v\\ \delta \omega\end{bmatrix}+\begin{bmatrix}1/m & 0\\ 0 & 1/m\\ 0 & d/I\end{bmatrix}\begin{bmatrix}F1\\ F2\end{bmatrix} \quad (4)$$

C. Stability and Controllability Checking:

The poles of the above system were found to be: {-4.4444, -0.3095, -0.3095}; which have negative values and accordingly it is stable.

By checking the controllability of the system it is found that the rank of the controllability matrix which is 3X3 equals to 3 i.e. it is full rank, and accordingly; the system is controllable. Therefore, the provided system is verified to be controllable and a controller can be designed to achieve the given requirements.

D. PID Controller:

The PID gains have been tuned using Ziegler-Nichols' tuning method. The integral and the derivative gains of the PID controller are firstly set to zero and the proportional gain is increased until the system starts to oscillate getting the oscillation period (T_u) and the ultimate gain (K_u). The obtained values for T_u and K_u are then used to set the proportional, integral, and derivative gains (K_P, K_I, & K_D) as follows:

$$K_P = 0.6 * K_u$$
$$K_I = 2*K_u / T_u$$
$$K_D = K_u * T_u / 8 \quad (5)$$

- Speed control:

The simplified transfer function for the speed in X direction is given by:

$$G_u(S) = \frac{1}{0.65+2.1\,S} \quad (6)$$

Using Ziegler-Nichols' tuning method, explained above, the control gains are as follow:

$K_P = 4.8$, $K_I = 16$, $K_D = 1$

- Position control:

The transfer function of X direction position is described by the following equation:

$$G_u(S) = \frac{1}{S(0.65+2.1\,S)} \quad (7)$$

By the same method, the PID controller parameters for position control are found to be:

$K_P = 6$, $K_I = 6$, $K_D = 2.5$

Fig. 5 shows the step response for the speed in X direction controlled by the gains calculated above.

Fig. 6 shows the step response for the position in X direction.

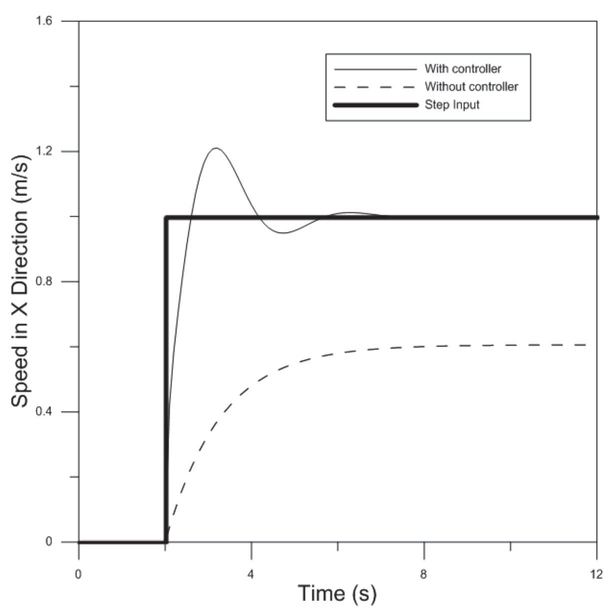

Fig. 5. Step response for speed in x direction

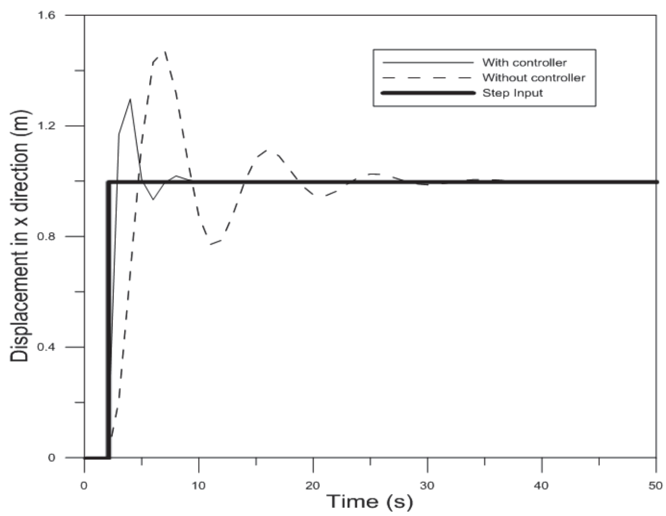

Fig. 6. Step response for postion iIn x direction

V. NAVIGATION SYSTEM

The navigation is the translation between two coordinates. So the navigation process starts by determining the targeted points and their Cartesian coordinates.

The considered vehicle is designed to work in two modes:-

- Remotely controlled mode.
- Completely Autonomous mode.

In the remotely controlled mode, RC remote control is being used directly with the actuators; while in the autonomous mode, an APM 2.5 board including a GPS and IMU sensors are used for autonomous navigation.

The motion of the hovercraft requires two stages, turning and moving forward. In the first stage, the hovercraft turns until it becomes in line with the point of interest. Once the first stage is achieved, the second stage will follow, such that the hovercraft moves until it becomes within a specific distance from the point of interest. The control algorithm will reduce the amount of error when the hovercraft is turning, as well as it is moving closer to the point of interest. Fig.7 shows a block diagram representation of hovercraft control system.

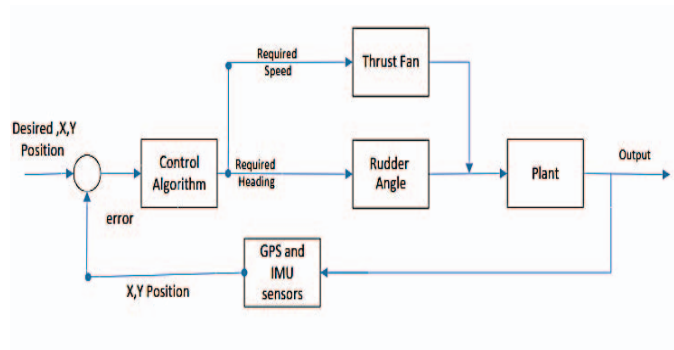

Fig. 7. Block diagram representation of hovercraft

The system shown in Fig. 7 has been checked both by practical testing and by simulation.

A. Practical Testing :

The flow of information starts with the user who inputs the Coordinates and the waypoints to the computer. Then the APM board read the sensors (GPS and IMU) values to begin the autonomous navigation. These values, such as position and speed, are passed to the control algorithm. The job of the control algorithm is to take the inertial measurements and determine what the actuator output should be, then it is translated into a PWM signal and passed along to the ESC's which directly control the actuators (servo and thrust motor). The lift fan is controlled directly by the RC controller. The actuator activity causes a physical result to the hovercraft which influences the state of the inertial sensors, starting the information flow process again. At this point, the APM also updates the ground control station with the sensor output which logs for later use. After the telemetry data for the parameter of interest is compared to the desired set-point a PID control is used with the control algorithm to minimize the overshoot.

B. Simulation:

Fig. 8 shows the SIMULINK Model of the model given by equations 1, 2, & 3 and the designed position controller following parameters data are considered:-

Mass of the hovercraft, m, = 2.1 kg; Translational viscous coefficient of friction, b, = 0.65 kg/sec.; Rotational viscous coefficient of friction, b_θ, = 0.03 kg m2/sec; Moment of inertia, I, = 0.045 kg m2; and the Friction coefficients are assumed to be μ_1 =0.1, μ_2 =0.01 and μ_3 = 0.004 [1].

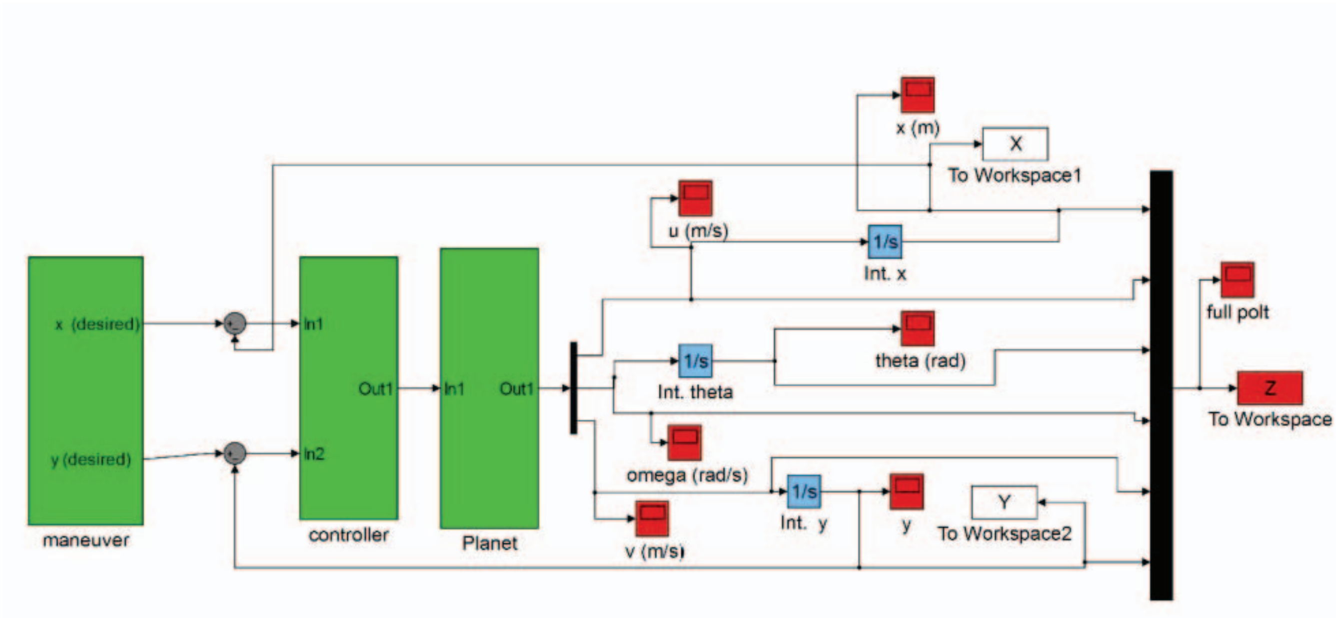

Fig. 8. SIMULINK closed loop model

C. *Trajectory Tests Results:*

Fig.9 & Fig.10 show the simulation and field testing results of two-point and three-point trajectory assignments. From both figures, it can be seen that the actual proposed vehicle could accomplish the targeted assignment in the autonomous mode with an error of 2 meters (18%) in the distance. This proves the idea and it should be noted that this significant error is due to the fact that the GPS considered is a low price commercial one and using more accurate one will result in more satisfactory results.

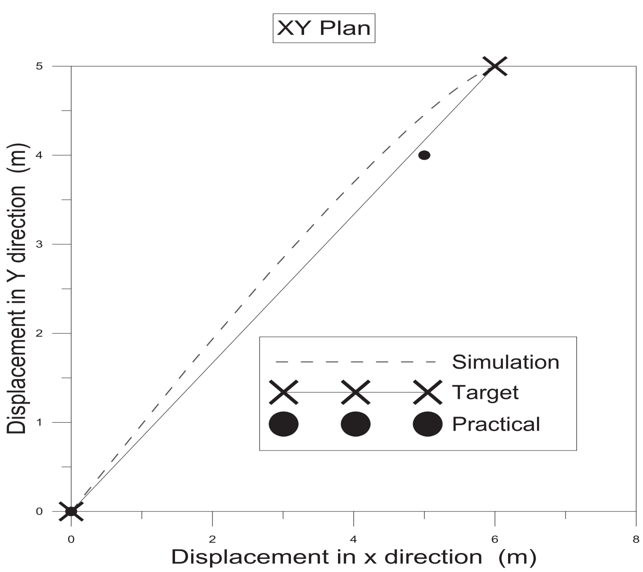

Fig. 9. Two point trajectory

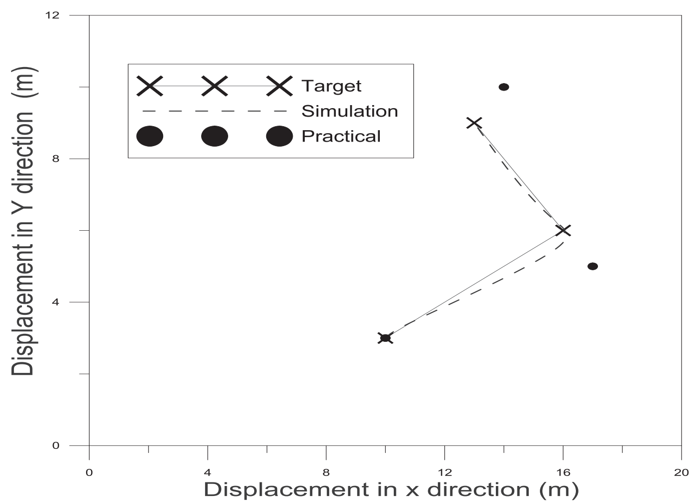

Fig. 10. Three point trajectory

VI. SPECIFIC RESISTANCE

This section illustrates the price to pay in terms of energy consumed represented by power efficiency for the hovercraft. In this work, an index is used to analyze the efficiency of the hovercraft which is the specific resistance (Ɛ). According to reference [11], the specific resistance of the vehicle (Ɛ) is given by:

$$\mathcal{E} = P/WV \tag{8}$$

Where;

W is the total weight of the vehicle (N),
V is the speed of the vehicle (m/s), and
P is the total power (Watt) which is given by:

$$P = P_l + P_t \tag{9}$$

Where;

P_l Lifting power (Watt), and

P_t Thrust power (Watt)

Experimental tests were applied to the proposed hovercraft with different ground surfaces. The hovercraft was run with different combinations of thrust & fan RPMs for a constant hovercraft speed. The specific resistance was calculated for each and the values of the RPM of thrust and lifting fans that give minimum specific resistance, $\mathcal{E}_{min}$ is considered. This condition corresponds to maximum efficiency of the hovercraft and accordingly minimum energy consumption.

A. Testing Results:

Fig. 12 shows the results by testing the hovercraft on a sandy road with constant speed 1 m/s. As shown in the figure; as the lifting fan RPM increases the thrust fan RPM decreases, the specific resistance decreases. This is until the lifting fan speed reaches 4800 RPM at which the specific resistance starts to increase again. Accordingly speeds of 4800 RPM and 3200 RPM for lifting and thrust fans give the minimum specific resistance which results in maximum efficiency and, accordingly minimum energy consumption.

Similar tests are repeated for different constant speeds. Table 1 gives the testing results for the RPM values for thrust and lifting fans that give minimum specific resistance corresponding to each speed considered. This can be used as a look up table to select the fan speeds for both lifting and thrust forces.

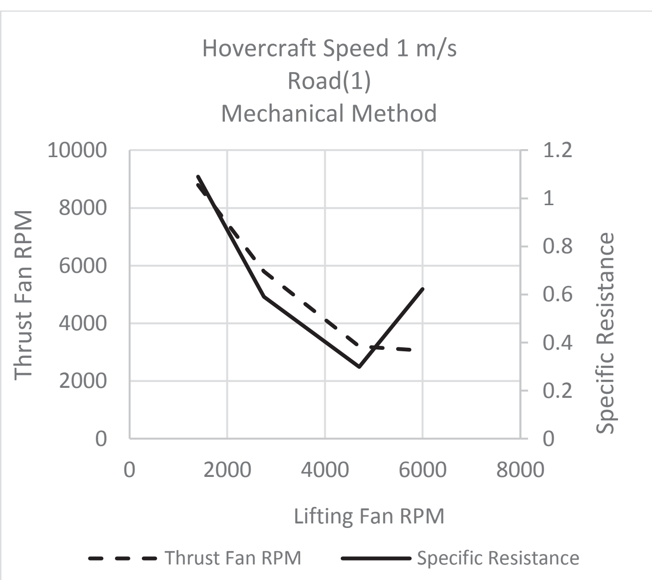

Fig. 12 Hovercraft Speed 1 M/S on Road 1 Test

TABLE 1 OPTIMUM SPECIFIC RESISTANCE (SANDY ROAD)

Hovercraft Speed (m/s)	Specific Resistance (optimum)	Lifting Fan RPM	Thrust Fan RPM
0.3	0.380754	1400	2800
0.5	0.280163	1400	3266.66 7
0.6	0.255016	1400	4800
0.8	0.263402	2750	3500
0.9	0.32634	4700	3100
1	0.299246	4800	3200
1.3	0.242975	4700	3500
1.6	0.318829	4700	4800
1.7	0.409199	4700	5800
1.9	0.442512	6000	4800
2	0.513142	6000	5800

Fig. 13 shows the minimum specific resistance for different speeds at different roads. The figure shows that the minimum specific resistance values depends not only on speed but also on the road type. More research is needed in this area.

B. Specific Resistance for Different Transportaions Means:

The specific resistance was determined in reference [11] for various transportation means not including the hovercraft vehicles. Fig. 14 shows the results obtained in present work plotted over the graph given by [11]. As shown in the Figure, the specific resistance is different in wide range from minimum of 0.004 to 0.05 (ships) to maximum of 10 to 12 for hexapod.

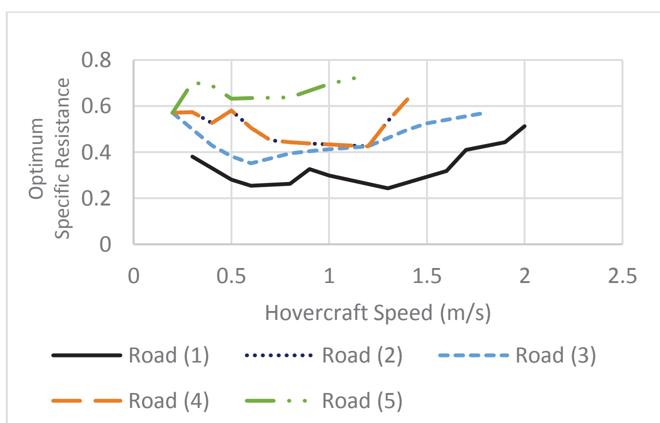

Fig. 13 Specific resistance optimum values

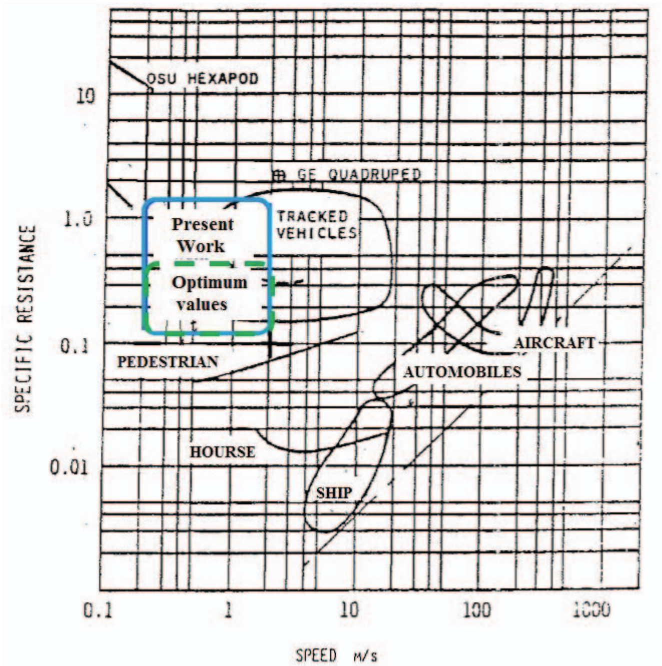

Fig. 14 Specific resistance for different transportations means [11]

The present work study of the considered hovercraft vehicle shows a full range of specific resistance from 0.2 to 1.2 while that for the optimum (minimum) ranges from 0.2 to 0.73.

VII. CONCLUSIONS

A small model of a hovercraft has been designed, implemented, and tested using three actuators for: lifting, thrust and steering. A navigation control system has been implemented in two different modes: Remotely and completely autonomous modes using GPS and IMU sensors and an electronic control unit to get location information and give the correct decisions for the actuators. Also a theoretical model has been developed and simulated in MATLAB/Simulink environment. For the considered model with data given in section (IV) and from simulation runs and experimental tests the following can be concluded:-

- The actual proposed vehicle could accomplish the targeted assignment in the autonomous mode with an error of 2 meters (18%) in the distance. This proves the idea and it should be noted that this significant error is due to the fact that the GPS considered is a low price commercial one. Using more accurate one will result in more satisfactory results.
- Using the proposed small real model, the energy consumed represented by power efficiency for the hovercraft has been investigated. This is carried out using an index called specific resistance.
- Based on these investigations, a look up table has been prepared to help in deriving an algorithm for controlling the RPM of lifting and thrust Fans based on the minimum optimism specific resistance. More work is still needed in this area.

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