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An Integrated Model for Supporting Better Fishering Vessel Design by Modeling Fish Schools Dynamics Ready for HLA

Stefano Filippi, Pietro Giribone, Roberto Revetria, Alessandro Testa

***Abstract*— This work is devoted to create an extension module for a naval manoeuvring simulator (Naval ++), which will allow the training of the crew of deep-water fishing vessels. The Authors were asked to develop the part relating to the “artificial intelligence” of marine biological entities: this should be capable of replicating the movement of a school of fish in a realistic way. This work also foresees an analysis of the main instruments used on-board and the problems inherent in their virtual simulation. Finally the papers outline a possible integration of the proposed model into an IEEE 1516 High Level Architecture Federation.**

***Index Terms*—Fish schools, Boids Modeling, Simulation, Echo-Sounder, Ship Design, HLA**

I. INTRODUCTION

FISING and aquaculture supplied about 147 million tons of fish in year 2010. Of these, 128 million were used as food for the world’s population, with a mean annual quota of 19 kg per person, which is the highest ever. The fishing sector is a source of income for millions of people all around the globe. The number of employees in fleets and aquaculture increased significantly during the three last decades, with an annual growth rate of 3.6% since 1980.

It is estimated that in year 2008 almost 45 million persons earned their living from work that is directly linked to the sector and that 12% were women. In 1980, there were 16.7 million workers: this data demonstrates an increase of 167%. It is also necessary to consider all work linked to secondary processing: this increases the number to 180 million. Finally, if we assume that each worker supports, on average, three people, we arrive at the figure of 540 million persons living from fishing, i.e. 8% of the world population.

The number of fishing vessels is estimated at about 4.3 million, a value that has remained constant in the past few years, of which 51% are motorised; the remaining 47% are located mainly in Asia (77%) and Africa (20%).

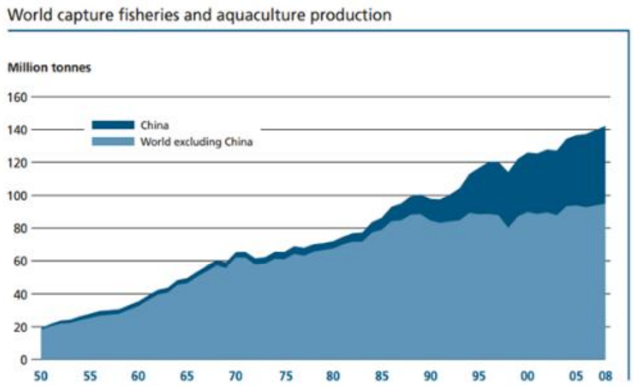

Fig. 1. World capture fisheries and aquaculture production (source FAO)

Currently, fishing depends significantly on fossil fuels, which are essential for the movement of the vessels and the functioning of all auxiliary systems onboard (processing and storage). This strong link is counter-productive for current environmental concerns and the consequent limitations on emissions that all governments are now launching and, in particular, links the cost of fishing to the cost of the fuel. As a consequence, commercial risks increase.

II. THE FISHING EXTENSION PROJECT

The objective of this work is to create a new module for the Naval++ manoeuvring simulator, capable of recreating the main operations of commercial fishing on the high seas. To that end, it is necessary to develop an instrument allowing optimal interfacing with the existing architecture (exploiting all the characteristics associated with navigation and the environment), and being to create and manage new elements.

The purpose of the simulator is to recreate the most common situations that the crew of a motorised fishing vessel may encounter: a series of possible behaviours of the school of fish is created on the basis of the choices activated by the user of the system. The functioning of the fishing simulator can be illustrated by the following diagramme:

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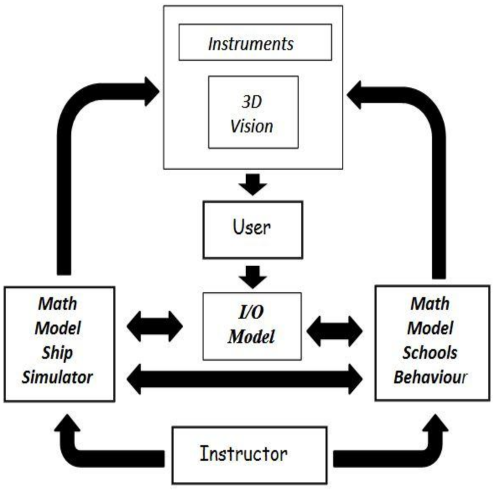

Fig. 2. General Naval++ model integrated with fish school simulator

As shown in the figure, the manoeuvring simulator and the fishing extension should become two perfectly complementary units: the instructor (the operator responsible for training) should interact with both systems, so as to be able to describe the behaviour of the schools of fish and the environment appropriately.

The heart of the new system is in "Mathematical Model SchoolBehaviour", which essentially includes two fields:

- Reciprocal behavioural dynamics of the elements within the school;
- Behavioural dynamics of the school in relation to the operations of the user and the surrounding environmental conditions.

This is then used to interact with the mathematical simulation model of the vessels and with the onboard instruments (I/O Model), both navigation and fishing instruments.

The creation of a code for describing the natural phenomena required quite a lot of precious time: after an initial bibliographic research and analysis phase and literature review, it was necessary to decide on how to develop the project, considering the time-frame and cost of the initiative. During this phase of the work, the choice of programming language was fundamental; C++ was eventually selected due to its validity and diffusion as a general-purpose code. This was then supported by Matlab, as it includes certain extremely useful functions.

III. The Behavioural Simulation Code

The theory encompassing the fundamental concepts involved in the schematization of the movement of groups is called "Flockingbehaviour": the first scholar of this subject, capable of creating a model resembling a calculator, was Craig Reynolds in 1986, with his "Boids" programme.

The model was constructed in an extremely simple way, exploiting three basic types of behaviour:

- Repulsion: the subject moves away from its neighbours, if under a defined distance;
- Alignment: the subject moves with its neighbours, if at a suitable distance;
- Cohesion: the subject approaches the other elements if too distant.

As can be seen, the heart of the system is the relation with neighbours: each element wishes to be as close as possible to the centre of the group but since, as happens in nature, the perception of the surrounding environment is limited, the elements are "content" with being in the centre of their neighbours.

This simple algorithm has thus been adapted to our purposes: the first step of the code developed by us was the definition of parameters, including the dimension of the space in which the school of fish moves, the number of elements participating in the simulation, and a whole series of parameters related to the speed of displacement, achievement and generation of the objectives; after all the basic settings are supplied, the code first generates the fish that are to form the various schools, considering them all as belonging to the same class, and then the objectives.

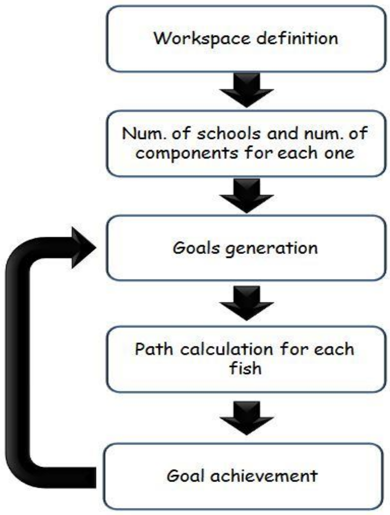

Fig. 3. Simulator logical model

At this point, the "guidance" dynamics of the elements start functioning, respecting the laws of "group motion". After the defined time has lapsed (or the objective has been achieved) a new goal is created automatically, consisting in recalculation of all the parameters relating to the movement. The cycle continues in this loop until the operator intervenes.

A. School generation

Considering the details of functioning, after the programme's launch data have been defined, the code can initiate its own work cycle.

The schools of fish are generated: these have been established in advance in terms of dimension and number; the n distinct elements, the fish, which compose the schools, are created in space and attracted to a common gathering point, a different one for each school of fish.

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The individual elements are objects that have the same characteristics (they originate from the same class C++); the principle characteristics are:

- Current position;
- Previous instant position;
- Current speed;
- Previous instant speed;
- Direction.

These parameters are fundamental for calculating the interactions between individual fish.

B. Generation of objectives

The purpose was to create a motion generator allowing the schools of fish to move within all the work area, in such a way as to generate totally random swimming paths, different for each element at each code launch.

The method functions in the following way:

- goals are generated in the work space;
- a single fish moves in the direction of the goal;
- while moving in the direction of the goal, the fish is expected to interact with the other members of the school.

In particular, in order to generate random goals, three equations are used (one for each spatial coordinate, X Y Z) in the form:

$$Goal[0] = (lenght\_x\_axis) \cdot (rand / rand\_\max) - (lenght\_x\_axis / 2) \quad (1)$$

However, in order to avoid that at each launch of the programme the generation of the same random numbers is generated, a code line is written that is able to link the time of the system (the time of the computer) to the generation function: In this way, different launch instants correspond to different generations of objectives (during every cycle, the "stand" function provides a new "seed" for the random generation of "rands").

C. Calculation of group paths and dynamics

In order to calculate the position of each element, at each step, in relation to its objective and the other components of the school, a function was created; the operation of this function is illustrated in Fig.4.

The first step is to update the variables of the previous cycle, in particular the position and speed; then, to calculate the distance between an element and the objective, using the following simple equation:

$$line\_to\_goal = global\_goal - oldpos \quad (2)$$

After which the progress of the element is evaluated in relation to the previous instant through:

$$pos = oldpos + oldvel \cdot dt \quad (3)$$

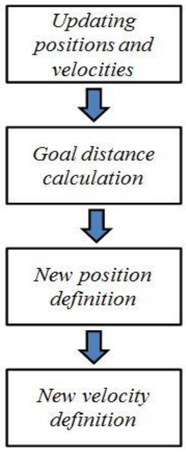

Fig. 4. Calculation of group paths and dynamics

And its speed:

$$vel = oldvel + targetdir \cdot dt \quad (4)$$

With a maximum value, however, beyond which the value is truncated. In the case where the new position differs from the previous one, a new direction vector is created:

$$direction = oldpos - pos \quad (5)$$

Moreover, the inclination angles of the fish are updated during the "swimming" phase (the inclination of the element various at each moment in time, or rather, the cone representing the element, in such a way as to simulate the swimming phase in the best possible way): being a simple simulation, these vary cyclically between two values, +angolo e –angolo.

Going back to the previous formulae, it is necessary to evaluate parameter "targetdir", as this parameter represents the real direction of the fish's movement (and the movement vector): in fact, as the fish is moving in an extremely crowded environment, it cannot move simply in the "line to goal" direction but must change direction so as to follow the rules of the school's movement or rather that of the Boids.

The process illustrated the function can be summarised by the diagramme in Fig.5.

For each step of the simulation, the ideal path linking each component to the objective is calculated, after which a cycle that calculates the neighbours of each fish commences: these neighbours are the elements that are at a distance of less than a set limit and have a path that crosses the path of the element under examination.

After all the neighbours have been noted, the code controls which ones are under a set distance value (thus entering the influencing area) and calculates an average distancing direction.

Thus, an ideal escape direction and an "escape priority" is defined, i.e. the importance of increasing the distance from the group compared to movement towards the objective. The smaller the distance the higher the "priority" value. Thus, the value obtained is subtracted from the level of maximum priority, generally set at 1.

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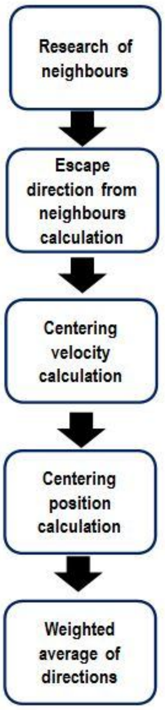

Fig. 5. Boids movements block model

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Having noted this value, if priority is still available, the code calculates an approach "priority" for the elements which, however, is less important compared to the previous one, and also calculates an ideal approach direction (both the priority and the direction are based on the orientation of the average speed vector of the neighbours compared to the element under examination).

A similar procedure is followed by evaluating the distance using the centre of gravity of the positions of the neighbours (this guarantees group compactness).

Finally, the final direction is calculated as the sum of the results of priorities and ideal directions, considering the residual priority as the priority that pushes towards the objective:

$$\begin{aligned} t\arg etdir &= (borders \cdot weight) + (\min\_\ dist \cdot weight) + \\ &+ (average\_velocity \cdot weight) + \\ &+ (line\_to\_goal \cdot weight) \end{aligned} \tag{6}$$

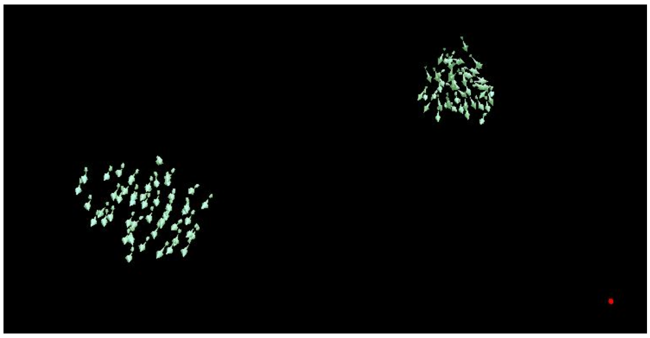

Fig. 6. 3D Virtual Reality GUI for schools behaviour validation

IV. From Schools to Ellipsoids

The code described has shown optimum and stable functioning: at a qualitative level, it optimally replicates a generic school of fish, even a large one.

In order to fulfil the requests of the customer, a mathematical structure was implemented that provides the same advantages as regards the emulation of group behaviour, but a lower calculation weight. Therefore, the school ellipsoid envelope was introduced: This is the minimum volume figure that is able to contain all the elements of each school, notably reducing the number of data elements memorized by the computer. In particular, for each n (optional fixed value, generally equal to 10) time steps, the software calculates this geometry that always assumes different dimensions, thus reproducing the dynamics of the school.)

A. Rotation ellipsoid

An ellipsoid is a closed quadratic surface, which represents the three-dimensional equivalent of an ellipse. Its initial equation, in Cartesian coordinates and with the axes aligned with the main ones, is as follows:

$$(x^2 / a^2) + (y^2 / b^2) + (z^2 / a^c) = 1 \tag{7}$$

This is a typical choice when it is necessary to envelope a cloud of points. Matlab was used to distinguish, at each step, the minimum volume, as it contains a special instrument that designs these objects rapidly.

A minimization function was drafted, centred around the "fmincon" command, the functioning of which foresees the setting of an equation to minimise, while varying specific unknown components and under established conditions.

A vector x was defined containing the six unknowns:

- x(1) x(2) x(3) are the three ellipsoid radii
- x(4) x(5) x(6) are the three centre coordinates

Thus, knowing that the volume of the ellipsoid is obtained from the following formula:

$$volume = 4/3 \cdot \pi \cdot a \cdot b \cdot c \tag{8}$$

Where a, b, c, are the three radii, this minimization function was chosen, excluding the multiplication constants.

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$$f = x(1) \cdot x(2) \cdot x(3) \qquad (9)$$

It was thus necessary to set the constraint equations: these were all characterised by non-linear inequality, in quantities equal to the number of elements constituting the school.
In order to establish these, reference was made to formulation within the Cartesian area of the ellipsoid:

$$\left[(x-x_0)^2/a^2\right]+\left[(y-y_0)^2/b^2\right]+\left[(z-z_0)^2/z^2\right] \qquad (10)$$

After all the positions of the fish were set in matrix Q [*nxm*], with *n* equal to the number of fish, their generic form was written:

$$C = \left[(Q_{i1}-x(4))^2/x(1)^2\right]+\left[(Q_{i2}-x(5))^2/x(2)^2\right]+ \\ +\left[(Q_{i3}-x(6))^2/x(3)^2\right] \qquad (11)$$

As the spatial distribution of fish varies, in order to have an idea of the school's compactness, a part of code was inserted in order to define the density of the ellipsoid's population.

This is calculated as follows:

$$Ro = n / volume \qquad (12)$$

To conclude, the calculation process, compared to an input of a matrix QQ [nxm], where n = number of fish, restores 7 values, six for the construction of the ellipsoid and the seventh for the definition of density.

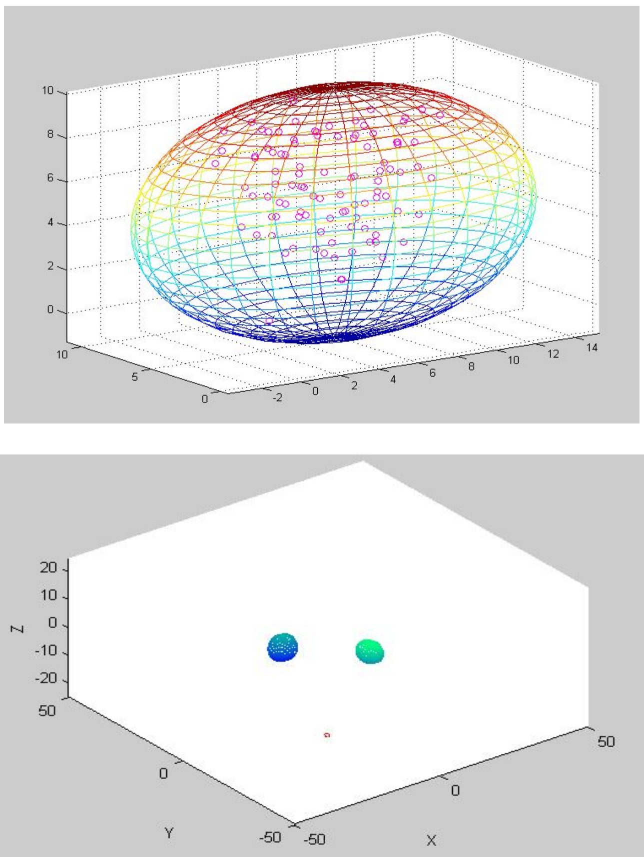

Fig. 7. 3D Example of a school envelope Two schools in space

V. ON-BOARD INSTRUMENTS: ECHO SOUNDER

The objective was to create a dynamic image able to replicate, as faithfully as possible, the images on the monitor of a real instrument for the purpose of analysing the seabed.

The point of departure of the work was the analysis of the onboard instruments of a vessel, while focusing on the main characteristics of echo sounders: having analysed the problem in a simplified way, it can be said that echo sounders emit a "cone" of acoustic waves that are reflected after reaching a body with a higher density than water; a suitable microphone collects such sounds and a microprocessor calculates the time between the emission and the return, thus calculating the depth.

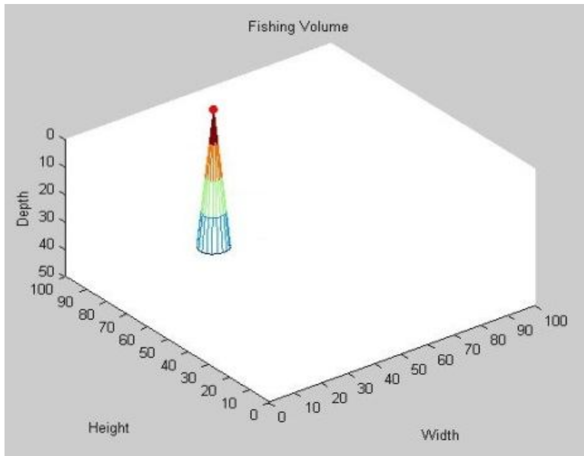

Fig. 8. 3D Representation of the vessel and the acoustic cone

A. *Dynamic representation of the vessel*

In order to represent the area of interest of the sonar in the best possible way, it was decided to schematize everything using a cone; the required parameters are as follows: basic radius, height and vertex angle (a result of the other two figures).
The code foresees generation via the introduction of a "grid" created with the points of area a at defined steps of the rotation height. This, as can be noted by reading the code is parameterised in such a way that its origin is at point B, i.e. the vector containing the position coordinates of the vessel, and its height is equal to the depth.

B. *Study of the sonar cone / schools of fish interference problem*

This is the heart of this part of the code, as it includes writing the necessary mathematical laws that would allow a correct intersection between the zone of interest of the sonar and the moving school of fish. Its correct structuring has required countless hours of work, including the development of various approach methods. It is necessary to recapitulate the information about the system in order to understand the complexity of the problem as much as possible:

- Area;
- Position of the vessel and geometrical characteristics of the cone, including the cone's mesh value;
- Ellipsoid construction parameters, centre and mesh values.

Avoiding an excessively heavy code was a major problem as the system studied has to function in real time and thus with very brief reaction times.
In order to obtain such results, at each step, the system considers that there is interference in cases where the distance between the axis of the cone and the centre of the ellipsoid is smaller than the radius of the cone at that height, and larger than one of the three radii of the ellipsoid.
After the mathematical laws regarding the intersection between the ellipsoids and the cone were written, we tried to reconstruct an echo sounder return signal graphically.

The work was carried out in two steps:
- Schematic visualisation of the signal;
- Graphic visualisation of the signal.

The first was fundamental for starting to understand the problem and assess the potential solutions; for each step, the cycle assessed whether there were any intersections between the sonar and the cone: in the affirmative case a dot (blue) was reproduced, corresponding to the depth of the centre of the ellipsoid, inside a “run area” and “depth” graphic, while in the negative case a red point appeared, corresponding to the seabed.
The second step consisted in providing a graphic that would correspond as far as possible to real echo sounders (introducing bands of various colours) and, moreover, a logic was introduced that, based on the density of the fish school, varied the dimensions of the image showing the position of the ellipsoid.
The result obtained showed optimum functioning and a degree of similarity closely resembling the real situation, as shown in the Fig. 9.

It is interesting to note how the density parameter influences the representation of the school of fish in the simulated echo sounder:

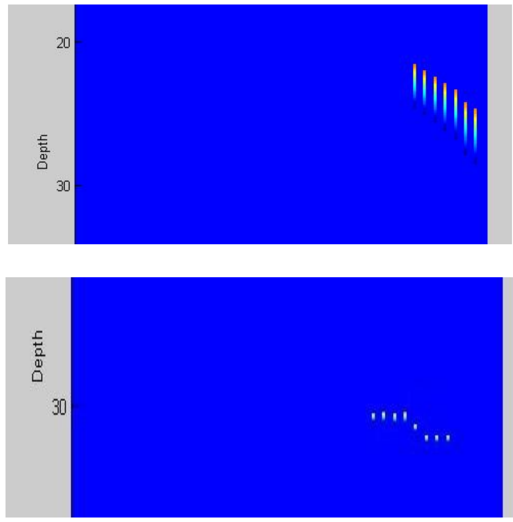

Fig. 10. Echo Sounder and Echo Cone GUI for validation purpose (details)

The two images show a comparison between how a signal produced by the intersection of the sonar cone with a very dense school of fish is described (visible on the left) and, therefore, represented by a small ellipsoid, and a low density school (visible on the right), represented by a large ellipsoid, with the number of school components being equal.

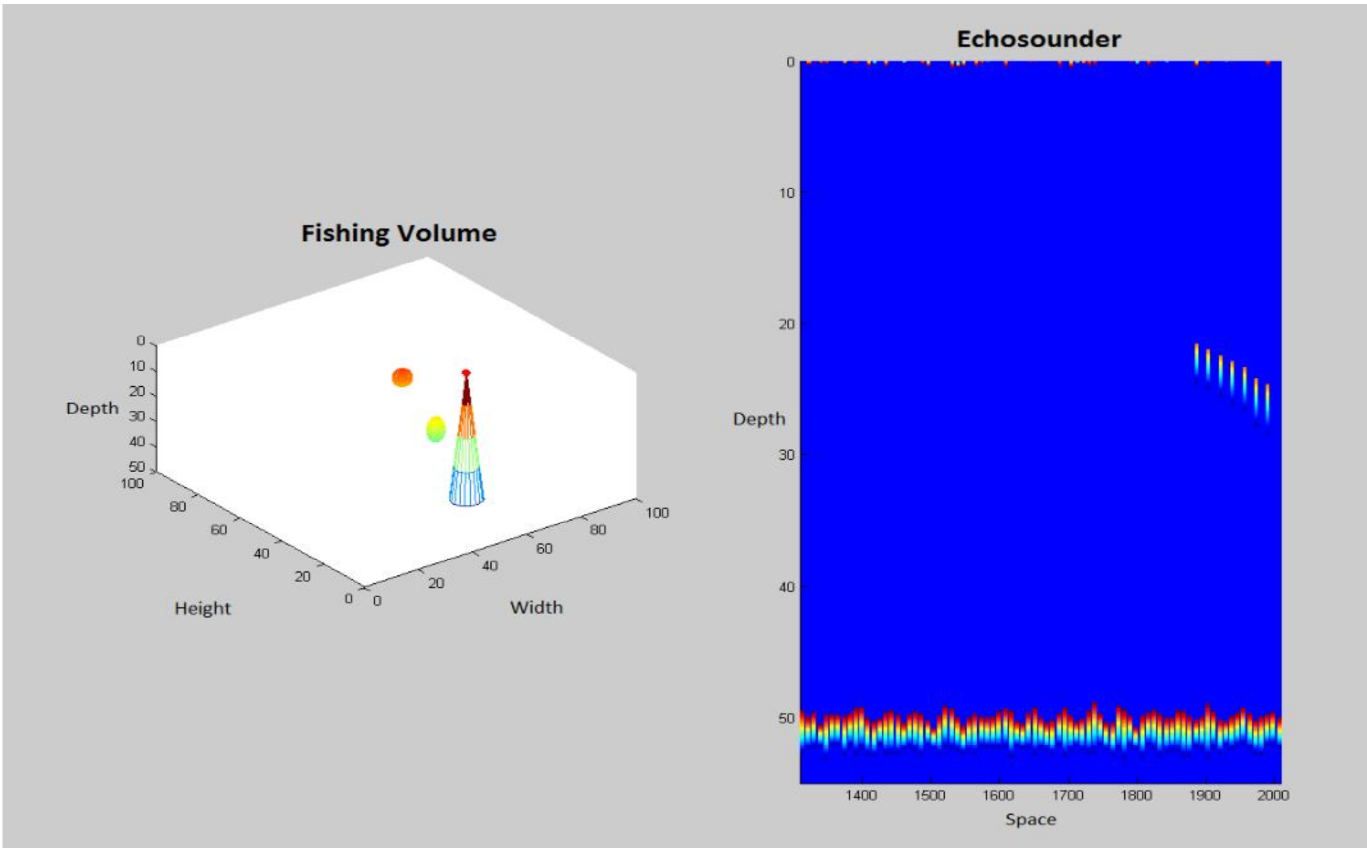

Fig. 9. Echo Sounder and Echo Cone GUI for validation purpose

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VI. Conclusion

The codes created in this activity have shown optimum functioning characteristics. Among these, the capacity to work in real time is of fundamental importance. During the entire programming phase efforts were made to maintain the simplest possible model, by eliminating or minimizing large calculation cycles: the final result has shown that it is possible to make the various components interact (especially the school of fish and the sonar) in a very quick and efficient way, without running into unpleasant problems or requiring high capacity calculators.

After the Fishing and FishFinder software systems were developed, it was noticed that their use would not only be valid within Naval++, but also as an autonomous system: it was observed that the school of fish, after being subjected to suitable biological validations, could be used to analyze the impact of the vessels (in particular as regards noise emitted by the engine and the instruments on board) on marine fauna. Therefore, this could allow its use not only in simulation but also in design, thus creating new and interesting scenarios for the future.

Moreover, other methods also exist for exploiting its potential: one of these consists in “unpacking” its components (school, sonar and vessel) and making it interact with external objects through distributed computation protocols, such as IEEE 1516 High Level Architecture (HLA). This allows the transformation of our code into one component, or set of components, capable of participating in very broad simulations (different objects can be used: vessels, aircraft, terrestrial transport, port units, etc.), with a high number of participants, located on different machines.

The current state of the work evidences the achievement of an excellent result as regards the interaction of the school’s elements, but it is not yet able to react to external stimuli that could compromise integrity and safety.

Nevertheless, development has already been pursued with the aim of developing these concerns: in fact, movement is assigned to a system for which the school is brought to move in a certain direction, currently set in a random way but, if external elements were to be introduced, able to compromise the safety of the school, it would suffice to develop a logic for the creation of objectives that would return the school to safety conditions (protection via escape concept).

To conclude, it can be seen how the bases used for the creation of this simulation module were created: a very flexible model was written, capable of emulating the motion of general biological marine entities, but already predisposed for the specific definition, and the issues relevant to the simulation of the instruments on board, which are fundamental for reproducing the right fishing conditions, were studied in depth.

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