Development of a demonstrator for predicting the operation of unmanned aerial vehicles on naval platforms

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Juan Carlos Carmona[1]*, Raúl Atienza[1] and José Ramón Iribarren[1]

[1] Siport21. C/Chile, 8. Edificio Azasol. Oficina 208. 28290 Las Matas (Madrid) SPAIN
e-mail: siport21@siport21.es, web page: http://www.siport21.com

ABSTRACT

The "System for Predicting the Operation of Unmanned Aerial Vehicles on Naval Platforms" (SPOVENT) project aims to determine the studies and developments necessary to obtain and characterise the data required to predict ship movements in waves in real time and, therefore, to be able to predict the optimum windows for recovering/landing UAVs.

The project was developed in two phases: the objective of the first one was the identification of the available technology applicable to the prediction of the 3D vessel motions during its operation plus the determination of maximum vessel motion limits in order to carry out the capture of UAVs in safe conditions; then came the development of two algorithms to predict the movements of the vessel depending on the waves that it will encounter during its navigation. After the completion of these initial phases, the validation and evaluation of the algorithms developed is carried out, followed by the development of the SPOVENT demonstrator, implementing the algorithm with best results.

To determine the algorithm which best predicts the time windows in which the UAV will be able to operate, the following evaluation and validation criteria are established: accuracy of the prediction of the operation windows, range of application, input data required for its correct operation, possibility of adaptation to different types of vessels and required calculation time.

Once the algorithm to be implemented in the demonstrator has been selected, a computer application is developed that shows the user the time windows to perform these operations with adequate safety. The design of the application ensures that user intervention is minimal, considering the operating conditions on a ship, including easy-to-read indicators and easily accessible buttons. Additionally, the demonstrator will be a tool to evaluate the operational criteria (STANAG) of different missions during navigation, by means of the ship's movement variables registered by an IMU sensor.

Keywords: Seakeeping; unmanned aerial vehicles (UAV); time domain; motions prediction.

NOMENCLATURE

M_{ij}	Mass matrix [kg]
A_{ij}	Added mass matrix [kg]
B_{ij}	Damping matrix [kg/s ; kg·m/s]
C_{ij}	Restoring coefficients matrix [kg/m ; kg]
$\ddot{\delta}_j$	Acceleration [m/s^2 ; 1/s^2]
δ_j	Motion [m ; rad]
$\dot{\delta}_j$	Velocity [m/s ; 1/s]
F_{EXC}	Wave excitation forces [N]

1. INTRODUCTION

The "System for Predicting the Operation of Unmanned Vehicles on Naval Platforms" (SPOVENT) project aims to determine the studies and developments necessary to obtain and characterise the data required to predict in real time the movements of the vessel caused by waves and, therefore, to be able to predict the optimum windows for recovering/landing UAVs.

Figure 1. UAV landing operations.

During the first phases of the project, the most appropriate technologies for wave detection, sea elevation time series and propagation were identified, and two algorithms were developed to predict the behaviour of the vessel underway (Iribarren, 2016). The first algorithm developed (Algorithm I) is based on the classical seakeeping theory (González Álvarez-Campana, 2010) and the second algorithm developed (Algorithm II) solves the problem of ship behaviour in the time domain by means of transfer functions. The methodology of this second method consists of modelling the ship behaviour and the excitation forces by using transfer functions, which allow obtaining the ship motions as a function of the wave height (De la Cruz, 2004).

After the development of both ship motion prediction algorithms, and according to the SPOVENT project schedule, the developed algorithms are validated and evaluated.

In order to determine the algorithm providing the best results in the prediction of time windows for UAV operation, the following validation and evaluation criteria are established:

- Validation criteria: accuracy of prediction of operating windows and range of application.

- Evaluation criteria: input data necessary for its correct operation, possibility of adaptation to different types of vessels, prediction accuracy and required calculation time.

The studies carried out during the development of the project are used for the evaluation. In the case of the validation process, the records of waves and ship movements obtained during the performance of seakeeping tests completed at CEHIPAR (Canal de Experiencias Hidrodinámicas de El Pardo) are used.

Prior to the validation of both algorithms, a calibration of the algorithms is carried out by analysing the accuracy of the results as a function of the variation of their adjustment parameters.

After validation and evaluation of both algorithms, the best performing algorithm is selected for implementation in the SPOVENT demonstrator.

2. CALIBRATION AND VALIDATION OF ALGORITHMS

2.1 Algorithm I

The first algorithm developed is based on classical seakeeping theory (González Álvarez-Campana, 2010). The first step in solving the problem is to determine the hydrodynamic characteristics of the ship from the hull shapes and the loading condition. These characteristics are determined from the incident wave, radiated wave and diffracted wave potentials. These values are obtained using a commercial potential flow analysis program, which allows to obtain the hydrodynamic characteristics of the ship.

By operating the equation of the ship's behaviour at sea and substituting the different forces present in the equation, an equation is obtained whose terms are known for each frequency of oscillation of the ship and direction of the waves, except for the ship's movements in its six degrees of freedom, which are the unknown to be obtained.

$$\sum_{j=1}^{6}\left[\left(M_{ij}+A_{ij}(\omega)\right)\cdot\ddot{\delta}_j(t)+B_{ij}(\omega)\cdot\dot{\delta}_j(t)+C_{ij}\delta_j(t)\right]=F_{EXC}(t) \quad (1)$$

Therefore, in order to solve the problem of the ship's behaviour at sea, it is necessary to know the sea elevation that the ship will encounter along its navigation during the interval in which the prediction is to be made in order to determine the forces that the waves generate on the ship. The problem has been solved by applying the impulse response theory proposed by Cummins, W.E. (1962) and making simplifications by using a state space (Pérez, 2009). The algorithm uses as input parameters the wave elevation time series and the predominant direction of the wave, as well as the vessel's ground speed.

2.2 Algorithm II

The second algorithm developed solves the problem of ship behaviour in the time domain by means of transfer functions. The methodology of this second method consists of modelling the behaviour of the ship and the excitation forces through the use of transfer functions, which allow to obtain the movements of the ship as a function of the wave height (De la Cruz, 2004).

$$[(M+A)\cdot s^2+B\cdot s+C]\cdot X=F_{EXC}(s) \quad (2)$$

To obtain the ship motions, the forces corresponding to the ship motions in six degrees of freedom are calculated. The forces corresponding to the motions are obtained by means of six transfer functions. Once the forces corresponding to each movement have been calculated, by means of new transfer functions, the ship's movements in six degrees of freedom are calculated. The adjustment of the functions is achieved by considering that surge, sway, roll and yaw motions are decoupled from each other; on the other hand, yaw and pitch are assumed to be coupled to each other. This coupling scheme has been selected to obtain a better approximation of the results.

2.3 Calibration and validation

The process of calibration and validation of the algorithms is carried out following the methodology developed within the project, which makes it possible to determine the optimal adjustment parameters and the range of application of each one of them, as well as the identification of corrective factors that allow the results to be improved.

The data used to carry out the calibration and validation of the algorithms are obtained from the seakeeping tests carried out at the Canal de Experiencias Hidrodinámicas de El Pardo (CEHIPAR) for this purpose. The data recorded in the tests are used both as input data to the algorithms (waves) and to compare the results obtained in the prediction calculations (movements).

Figure 2. Calibration and validation tests at CEHIPAR.

The aim of the calibration process is to obtain the parameter values of the algorithms that give the best results. During this process, the influence of each parameter on the calculations performed by the algorithms is also analysed. To carry out the calibration, a representative run is selected for each course, for which a sensitivity analysis of the adjustment parameters is carried out, varying them in a defined interval, after a prior study of the influence of each of the parameters on the results.

In order to select representative runs, which allow a correct calibration of the algorithms and include the whole range of encounter frequencies tested, all the runs carried out by CEHIPAR are classified into several groups, according to their encounter frequency. Within each group, one run is selected as the main run, which is used to calibrate the algorithm, while the rest of the runs are used for validation, i.e. the selected parameters are used to check whether the results obtained are valid in all cases. Run clustering is performed for each of the tested courses. It should be noted that the grouping of strokes by encounter frequencies makes it possible to establish application ranges, since it is a function of the ship's speed and the period of the swell (fundamental parameters of the ship's behaviour at sea).

For both algorithms, we start by analysing the course corresponding to head seas, since for this course the balance is not considered and therefore there are fewer parameters susceptible to variation. Once the main courses have been selected, the calibration is carried out by analysing the differences detected between the operating windows of the time series of movements recorded in CEHIPAR and those calculated by the algorithms.

To determine the operation windows, the time intervals are determined in which none of the variables exceed the established limits, thus ensuring that the UAV can perform the shot safely. The limits used as a reference are as follows (the algorithm allows defining other values):

Table 1. Limits for UAV landing

Movement	Limit
Roll	5º
Pitch	3º
Vertical velocity	1.0 m/s

Since the speed limit refers to the UAV take-off point, this point is considered to be 60 m aft of the ship's centre of gravity, and therefore the vertical velocities at this point are calculated.

For the analysis of both time series, an auxiliary program is developed, which will be implemented in the demonstrator. The program automatically obtains the starting time of an inoperability window (time in which one of the established limits is exceeded) and its ending time (time in which the value of the movements is below the established limits), both for the movement records made in the CEHIPAR tests (values considered as reference values) and for the time series calculated by the algorithms.

The time differences of the inoperability windows of CEHIPAR and the algorithms are obtained by subtracting the initial and final time of each inoperability window obtained with the algorithms from the times obtained with CEHIPAR: $t_{0\_CEHIPAR} - t_{0\_Alg}$ $t_{1\_CEHIPAR} - t_{1\_Alg}$

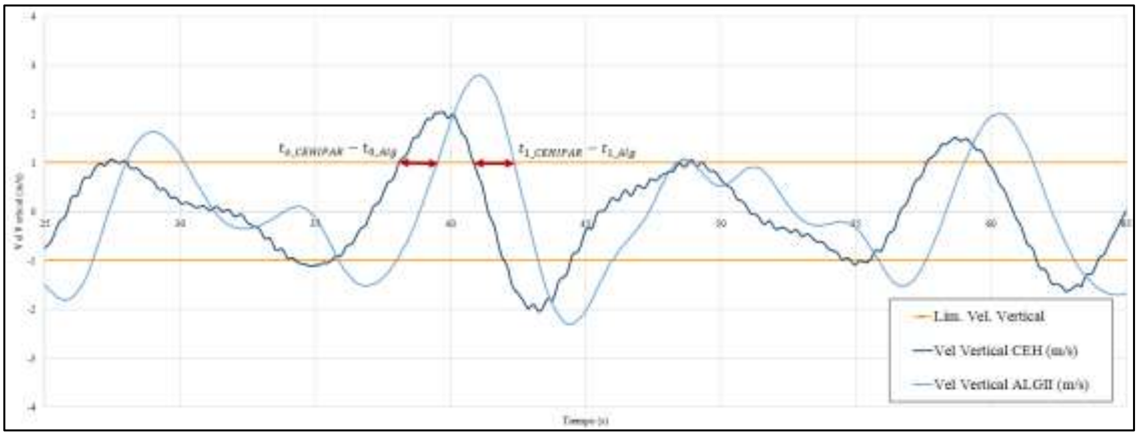

Figure 3. Determination of time differences

Therefore, as long as the initial time difference is positive and the final time difference is negative, the result will be on the safe side, since the inoperative window calculated by the algorithm will contain the CEHIPAR window.

Since the UAV requires a minimum time to perform the operation, in case the time between two inoperative windows is less than the time required to perform the operation of the UAV, the program developed joins both windows, considering the initial time of the first one and the final time of the second one. Although the operation time required by the UAV is a variable that can be defined in the analysis program developed, the calibration process has been carried out by setting a minimum time of 15 seconds.

After the initial analysis of the time series calculated by the algorithms, it is observed that a correction of the amplitude of all the calculated movements is necessary. Therefore, the analysis program calculates a correction factor that approximates the value of the results of the movements obtained from the algorithms. This factor is obtained as the quotient between the maximum value of the time series of the movement measured in CEHIPAR and the maximum value of the time series of the result of the algorithm to be corrected. A factor is calculated for each movement of the vessel by multiplying the time series of each of the movements calculated by the algorithm by its corresponding factor. Therefore, together with the analysis of the differences between recorded and calculated windows, the number of windows and the pitch and vertical speed factors are taken into account (the closer they are to 1, the more accurate the algorithm calculations will be).

The figure below shows the calibration scheme used:

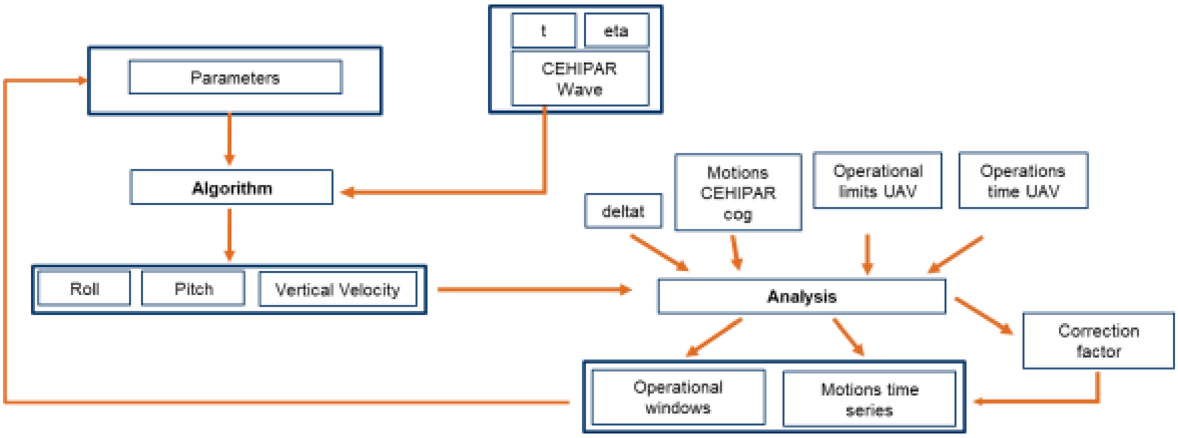

Figure 4. Calibration process outline

Once the calibration process has been completed, providing the value of the optimal adjustment parameters, the validation process is carried out, which is divided into two stages:

- In the first stage, the optimal adjustment parameters are applied, for each of the encounter frequencies, to all the runs belonging to the same group and the differences between the initial and final times of the predicted windows with those resulting from the analysis of the CEHIPAR tests are analysed, as in the calibration process.

- In the second stage, the time series are analysed using an analysis program included in the demonstrator. This second stage makes it possible to evaluate and determine whether there are times when the algorithms predict windows of operation in which the CEHIPAR recorded movement exceeds the established limits. This new auxiliary program determines the intervals in which the predicted movements are below the established limits.

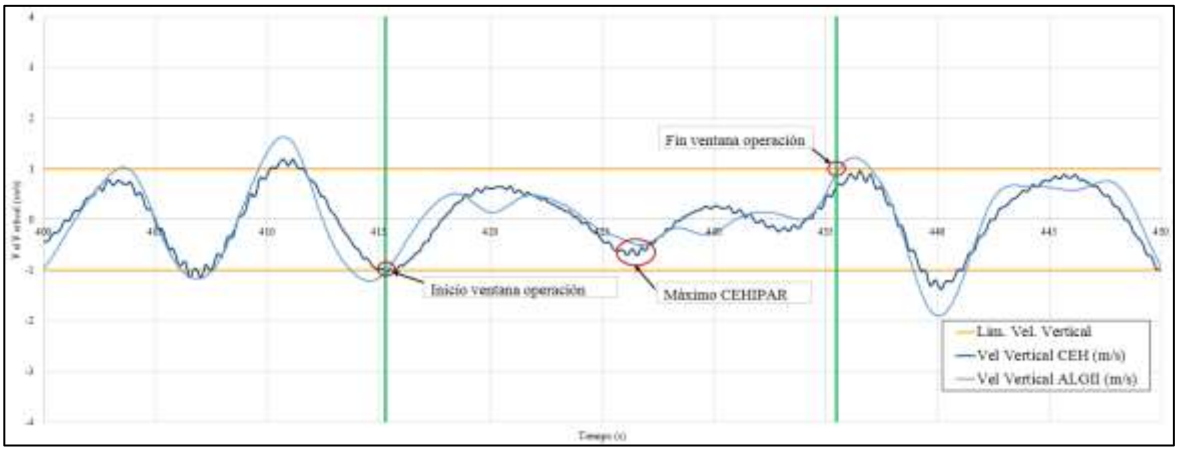

Figure 5. Determination of operating windows

3. ALGORITHMS EVALUATION

Once the calibration and validation processes have been completed, the algorithms are evaluated, considering the following criteria: input data required for their correct operation, possibility of adaptation to different types of vessels, results obtained (confidence in the predictions and number of predicted operating windows) and calculation time.

Once the different parameters have been evaluated, a decision table is generated to select the algorithm to be implemented in the demonstrator.

Table 2. Decision table.

	Algorithm I	Algorithm II
Need for physical model testing	=	=
Need for numerical simulations	=	=
Previous data required	=	=
Adaptation to different vessels	=	=
Calibration and validation time	=	=
Equality of operating limits	=	=
Equality of adjustment factors	=	=
Calculation time	-	+
Confidence in predictions	=	=
Number of operational windows detected	+	-

The decision matrix identifies that Algorithm I has the best performance in determining the number of windows and, since this factor is the most important for the objectives of the project, this algorithm is selected for implementation in the demonstrator.

4. DEMONSTRATOR DEVELOPMENT

The demonstrator is developed using the latest version of Visual Basic as the platform for the graphical interface. The calculation modules of the algorithm have been compiled in dynamic libraries (DLL) written in C++, which are used by the demonstrator to perform the necessary calculations.

The application developed manages both the information required to perform the calculations and the information to be displayed to the user so that he/she can make the decision to perform the landing operation with an adequate safety margin. The general operation of the application is summarised in the following diagram:

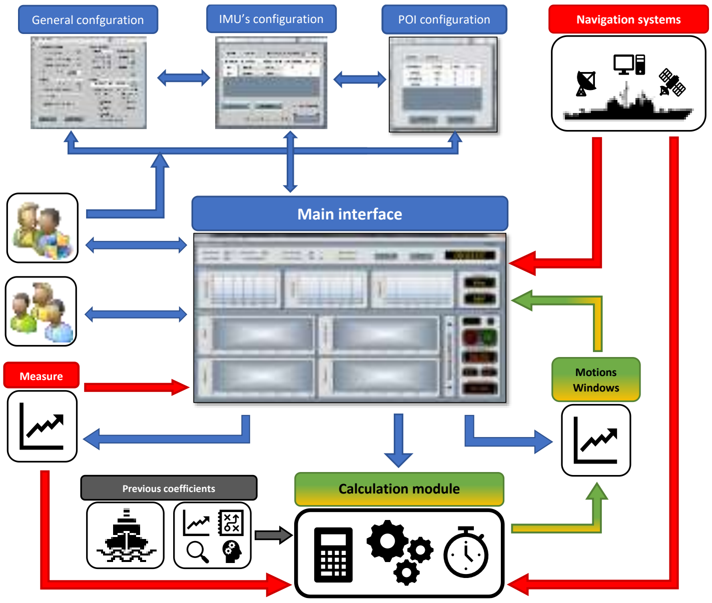

Figure 6. Demonstrator flowchart

The calculation module has three sub-modules: initialisation, movement prediction and window prediction. The movement prediction module performs the most complex calculations, which are used to obtain the motion time series by means of Algorithm I. The initialisation module only works during the initialisation phase. It is responsible for readjusting the necessary parameters, both in the motion prediction module and in the window prediction module, in order to obtain the most accurate window prediction possible.

The window prediction module analyses these time series to identify operative windows, based on the configured operability criteria. This same module returns the movement prediction time series along with the window prediction for display on the screen. Once the initialisation has been completed, it is possible to go into operation mode. In this mode, the application manages the information provided by the sensors and the vessel's hydrodynamic coefficients previously obtained to display the operating windows obtained on the main interface, indicating both the time required to reach the window and the time remaining once it has been reached. The interface clearly shows the operative windows, indicating with a highly visible light signal whether or not it is advisable to carry out the operation. This requires a wave prediction at the vessel's centre of gravity sufficiently in advance to allow the calculation of the predicted movement.

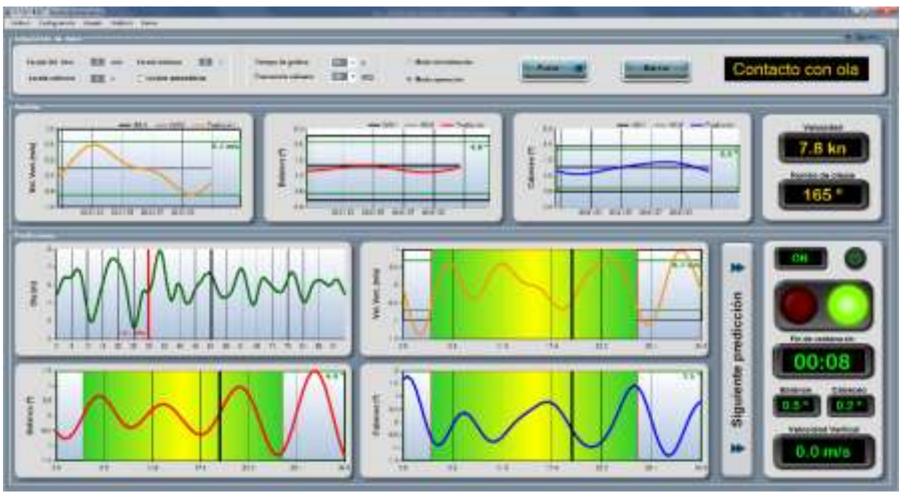

Figure 7. Demonstrator interface

5. CONCLUSIONS

After completing the process of calibration, validation and evaluation of the two algorithms developed for the prediction of the ship's seakeeping, within the SPOVENT project, Algorithm I, based on the classical seakeeping theory, was selected for implementation in the demonstrator.

During the analysis process it has been detected that the most limiting factor for UAV operation is the vertical speed of the flight deck.

It is highlighted that, although at the beginning of the project a sea state 4 was set as a maximum to verify the feasibility of the prediction system, the developed algorithms allow the identification of operation windows up to sea state 5.

The developed application demonstrates that it is possible to implement in a functional way a movement prediction software that can be used to provide safety in UAV landing operations, indicating concisely the time intervals in which it is recommended to perform the operation. The application uses a calculation algorithm previously validated and calibrated with seakeeping tests with a scale physical model, so that, by carrying out an initialisation to correct scale effects, results will be obtained with similar precision to that shown in the validation.

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