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The efficient use of wind force in sailing procedures onboard Tall Ship "Mircea"

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Abstract. The phenomenon of air mass movement is caused by the uneven distribution on the earth's surface of their thermal and pressure values. The uneven distribution of pressure in the horizontal direction is due to the combined action of thermal and dynamic causes and produces a movement called wind. Air temperature differences create different densities, which leads to maximum and minimum barometric pressure differences. The movement of air from a high to a low pressure area is called wind.
This research presents the efficient applicability of wind force in sailing procedures onboard sailing ships. For the practical view of this study, the Tall Ship "Mircea" sails are referred to.
Key word: Tall Ship, bracing, masts, spars, rigging, sailing surface.

1. Introduction

The intended field of applicability of the present paper is the theory and practice of seamanship among the sailing ships during their specific and unique missions on the sea.

„Mircea" Tall Ship is a Romanian three-masted bark, built in 1938 in Hamburg by the Blohm & Voss shipyard as a training vessel for future officers and petty officers of the Romanian Navy. As propulsion systems, the ship has a Mak Diesel engine with a power of 809 kW and the ship's sail surface. [1, 2]

Masts, spars, and sails of a three-masted bark (**Figure 1):**

A – bowsprit;

B – foremast;

C – main mast;

D – mizzen mast.

The ship's sails are shown in **Table 1**.

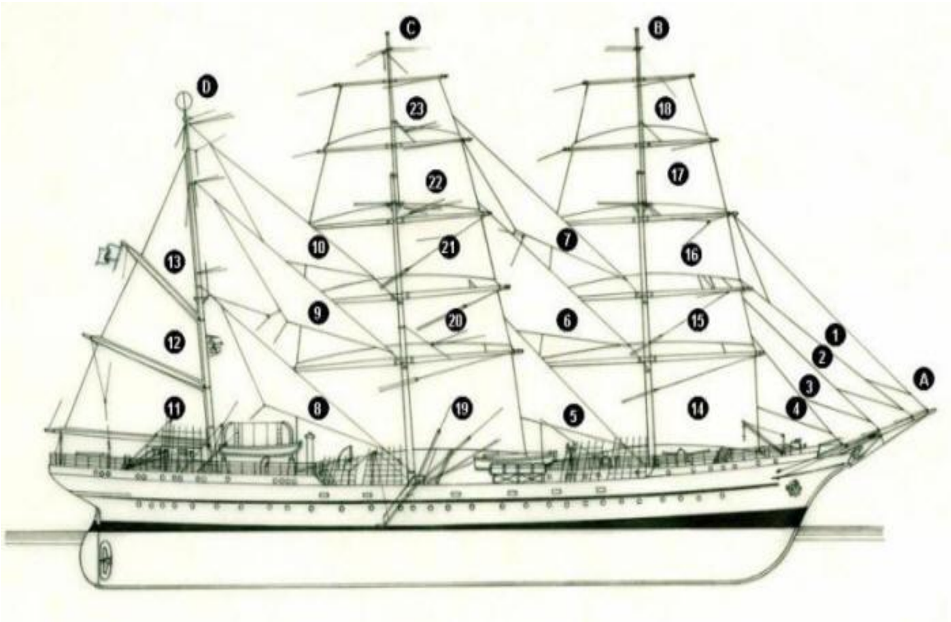


Figure 1. Masts, spars and sails of a three-masted bark [1]

Table 1. Ship's sails [1, 2]

1 – flying jib	2 – outer jib
3 – inner jib	4 – fore topmast staysail
5 – main topmast staysail	6 – main topgallant staysail
7 – main royal staysail	8 – mizzen staysail
9 – mizzen topmast staysail	10 – mizzen topgallant staysail
11 – lower mizzen sail	12 – upper mizzen sail
13 – gaff topsail	14 - foresail
15 – fore lower topsail	16 – fore upper topsail
17 – fore topgallant	18 – fore royal
19 - mainsail	20 – main lower topsail
21 – main upper topsail	22 – main topgallant
23 – main royal	

Masts and rigging:

- masts: foremast, main mast, mizzen mast, bowsprit;
- yards: - fore mast: foresail, fore lower topsail, fore upper topsail, fore topgallant, fore royal;
  - main mast: mainsail, main lower topsail, main upper topsail, main topgallant, main royal.
- booms and gaffs (on the mizzen mast): mizzen boom, lower gaff, upper gaff. [1, 2, 3]

The sails can be of several types:

- square;
- triangular: jibs and staysails;
- lower and upper mizzens. [1, 2, 3]

This paper aims to study the efficient use of wind in sailing onboard the TS „Mircea" and programing a prototype capable of orienting the ship's yards as accurately as possible and in a short time, to capture the most efficient force of the wind on the ship's sail surface. Implementing an automatic bracing system onboard sailing ships would bring a variety of advantages, among which the optimization of the time given to the prior activities to sailing, lowering the risk of accidents in working aloft, and reducing the number of personnel who are used for these activities.

2. Materials and Methods

2.1. Trimming Notions

To brace (trim) means to adjust yards so that the sails occupy the desired position depending on the wind's direction.

Onboard TS "Mircea" there are 3 ways to control the wind:

- strong wind: The wind blows so hard that the wind edge of the main royal and topgallant sail flutter. The wind can blow from a bearing of 6 points port side/starboard side.
- tight wind: The wind blows so that all the sails are full. The sheet corner of the main royal sail flutters. The wind can blow from a bearing of 6,5 points port side/starboard side.
- light wind: All sails catch the wind well. The wind blows from a bearing of 7 points port side/starboard side. [1]

The yards are trimmed in the following positions (**Figure 2**):

1. braced square;
2. one point on a starboard tack;
3. two points on a starboard tack;
4. three points on a starboard tack;
5. braced sharp (four points). [4, 5, 6]

When the ship has a large crew, the yards can be trimmed at the same time. In special situations, the masts will be adjusted one by one. To orientate a yard in the desired ship side, 2 groups of people are needed: those who will pull the yard on the indicated board and those who will ease the yard in the opposite board. [6, 7, 8]

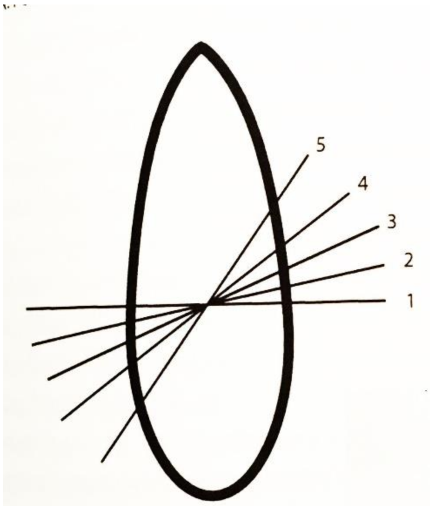


Figure 2. Trimming positions

2.2. Project Overview

The project object was to create a device capable of orienting each yard simultaneously, to benefit from the maximum potential of the wind in sailing. The system was made to brace the square sails, the maximum bracing angle being 35^0 on one side of the ship and the other (55^0 - 90^0, 90^0 - 125^0 Port side/starboard side). The maximum potential of the wind in sailing was considered to be reached when the angle between the true wind direction and the direction of the yard is 90^0. The system can be fixed under each yard at its base. [9]

The AutoSailing device is a prototype based on an electromechanical system, designed to orient the yards with a minimum crew and in a short time. The main purpose of the device is to orient the yards according to the direction of the true wind.

2.3. Project Designing

The programming environments used to design the project are Visual Studio and Arduino IDE [10, 11]. The application made in Visual Studio calculates the data of the true wind (direction and speed), having as input parameters the data about the ship (course and speed), from DGPS or GPS Compass (in the given application are manually entered) and about the apparent wind measured with the anemometer on board the ship (in the given application are manually entered).

Input data:

- Ship's course (degrees);
- Ship's speed (Kn);
- Apparent wind direction (degrees between 0^0 - 180^0 – Port/Starboard);
- Apparent wind speed (Kn);
- Wave height (m).

Output data:

- True wind direction in a circular system (degrees);
- True wind direction in quadrant system (degrees – Port/Starboard);
- True wind speed (Kn);
- Sea condition (according to the Beaufort scale);
- Wind condition (according to the Beaufort scale).

Controls to servo mechanisms:

- Yard position (current yard position);
- The condition of the sails (the system does not have an integrated sensor to indicate the condition of the sails – set or doused);
- Optimal direction of the yard (angle and ship's side in which the yard is braced);
- Optimal yard condition (braced or square).

To run the application input data must be entered and the Compile button must be pressed. Following the calculations, the application will show the output data. To see the current position of the yards, press the Get Servo button and by Set Servo, it will be sent the control command to the calculated optimal position. The application can run on a workstation with Windows operating system. The application also has the facility to graphically display the wind vector composition, by pressing the Graph button and then Plot.

2.3.1. Calculation Algorithm:

By entering the input data, the software calculates the actual wind data by the vector method. The apparent wind direction and the ship direction are decomposed on the two axes (X and Y) in the coordinate system (XOY), by trigonometric functions [12]:

$$\overline{X_{Vn}} = |\overline{V_n}| \cdot \cos \widehat{D_n} \cdot \pi/180 \tag{1}$$

$$\overline{Y_{Vn}} = |\overline{V_n}| \cdot \sin \widehat{D_n} \cdot \pi/180 \tag{2}$$

$$\overline{X_{Vap}} = |\overline{V_{ap}}| \cdot \cos \widehat{D_{Vap}} \cdot \pi/180 \tag{3}$$

$$\overline{Y_{Vap}} = |\overline{V_{ap}}| \cdot \sin \widehat{D_{Vap}} \cdot \pi/180 \tag{4}$$

After the decomposition of the vector, the direction of the true wind is calculated by the arctangent trigonometric function (atan2 in the C ++ language).

$$\overline{D_{Vr}} = 90^0 - \text{arctg}((\overline{Y_{Vn}} - \overline{Y_{Vap}}) / (\overline{X_{Vn}} - \overline{X_{Vap}}))) \cdot \pi/180 \tag{5}$$

The true wind velocity is equal to:

$$|\overline{V_r}| = \sqrt{\left(\overline{Y_{Vn}} - \overline{Y_{Vap}}\right)^2 + \left(\overline{X_{Vn}} - \overline{X_{Vap}}\right)^2} \quad (6)$$

The wind condition is given according to the true wind speed by the Beaufort scale, and the sea condition is interpreted according to the wave height.

The relative bracing angle is equal to:

$$\widehat{U}_r = \widehat{D_{Vr}} - \widehat{D_n} \quad (7)$$

If $\widehat{U}_r$ is in the (145^0, 180^0) interval, it results that the yards will be braced to port with an angle equal to:

$$\widehat{U}_b = 180^0 - \widehat{U}_r \quad (8)$$

If $\widehat{U}_r$ is in the (180^0, 215^0) interval, it results that the yards will be braced to starboard with an angle equal to:

$$\widehat{U}_b = \widehat{U}_r - 180^0 \quad (9)$$

If the relative bracing angle is not in these two intervals, it results that the sails must be doused and the angle of the bracing angle is 0^0 (the yards are perpendicular to the longitudinal axis of the ship).

*2.3.2. Example (***Figure 3***)*

Input data:

- Ship's course = 200^0;
- Ship's speed = 30 Kn;
- Apparent wind direction = 120^0 Port;
- Apparent wind speed = 30 Kn;
- Wave height = 7 m.

Output data:

- True wind direction in a circular system = 50^0;
- True wind direction in quadrant system = 30^0 Stern-Port Side;
- True wind speed = 51,96 Kn;
- Sea condition = agitated (grade 4 Beaufort);
- Wind condition = storm (grade 10 Beaufort).

Controls to servo mechanisms:

- Yard position: the yards have not been braced so far so their position is neutral - 900;
- The condition of the sails: Not know;
- Optimal direction of the yard: 300 Starboard;
- Optimal yard condition: braced.

The graphical representation of the true wind can be seen in **Figure 4**.

Given this example, the yards must be braced sharp in the starboard side. (**Figure 5**)

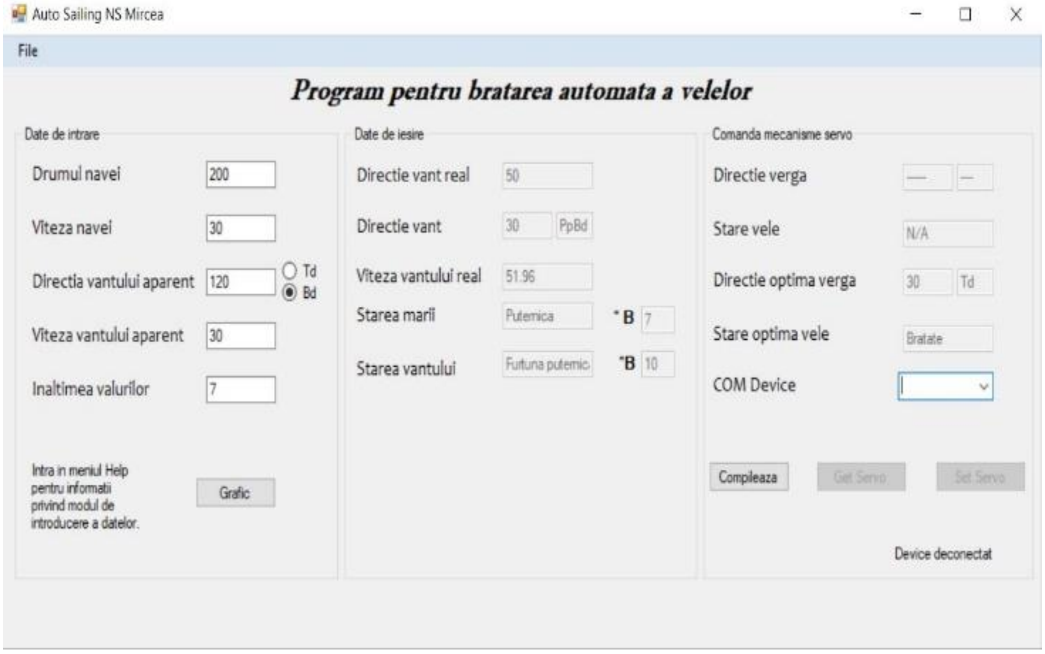


Figure 3. The application display for the given example

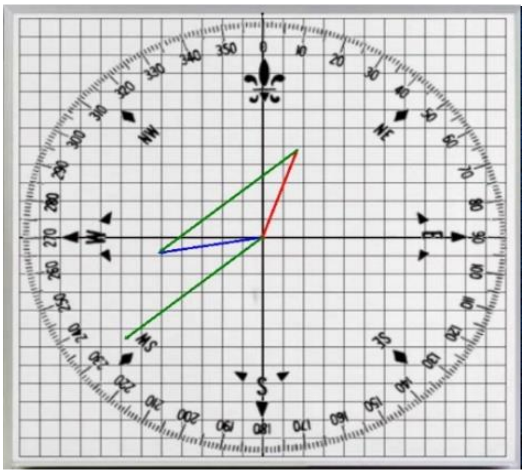


Figure 4. The graphical representation for the given example

Figure 5. The yards are braced sharp in the starboard side

3. The Implementation of the Automatic Bracing System onboard TS "Mircea" Analysis

3.1. General Information

Through the "Auto Sailing NS Mircea" application the TS Mircea yards can be orientated depending on the wind direction. The mechanical action of the yard is performed by a motor. The calculation of the minimum power required to adjust the largest yard was made in this chapter.

The following data were used for future calculations:

- maximum length of a yard = 24 m;
- maximum sailing surface of one sail = 178 m^2;
- maximum bracing angle = 35^0 = 0.6 rad;
- minimum bracing time = 60 s;
- maximum bracing time = 300 s.

3.2. *Wind Dynamic Pressure Calculation* **(Table 2*)***

The reference value of the wind dynamic pressure, q_b, can be determined by the relation:

$$q_b = \frac{1}{2} \cdot \rho \cdot v^2_b \ (kN/m^2): \qquad (10)$$

q_b = wind dynamic pressure (N/m^2);
ρ = air density (ρ = 1,25 kg/m^3);
v_b = the reference value of the wind speed (m/s).

Table 2 – Wind dynamic pressure calculation

No.	Wind speed (m/s)	Wind speed (Kn)	Beaufort scale	Wind dynamic pressure (N/m2)	Wind dynamic pressure (kN/m2)
1	5	10	3	15,65	0,01
2	10	20	5	62,5	0,06
3	15	30	7	140,625	0,14
4	20	40	8	250	0,25
5	25	50	10	390,625	0,39
6	30	60	11	562,5	0,56

3.3. Wind Force Calculation (**Table 3)**

$$F = p \cdot S \ (kN) \qquad (11)$$

F = wind force (kN);
p = wind dynamic pressure (kN/m^2);
S = sailing surface (m^2).

Table 3 –Wind force calculation

No.	Wind dynamic pressure (kN/m^2)	Sailing surface (m^2)	Force (kN)
1	0,01	178	1,78
2	0,06	178	10,68
3	0,14	178	24,92
4	0,25	178	44,5
5	0,39	178	69,42
6	0,56	178	99,68

3.4. Engine Torque Calculation **(Table 4**)

$$Mm = F \cdot b \ (kNm) \qquad (12)$$

Mm = engine torque (kNm);
F = force (kN);
b = distance = 12 (m).

Table 4. Engine torque calculation

No.	Force (kN)	Distance (m)	Torque (kNm)
1.	1,78	12	21,36
2.	10,68	12	128,16
3.	24,92	12	299,04
4.	44,5	12	534
5.	69,42	12	833,04
6.	99,68	12	1196,16

3.5. Engine Power Calculation (**Table 5**)

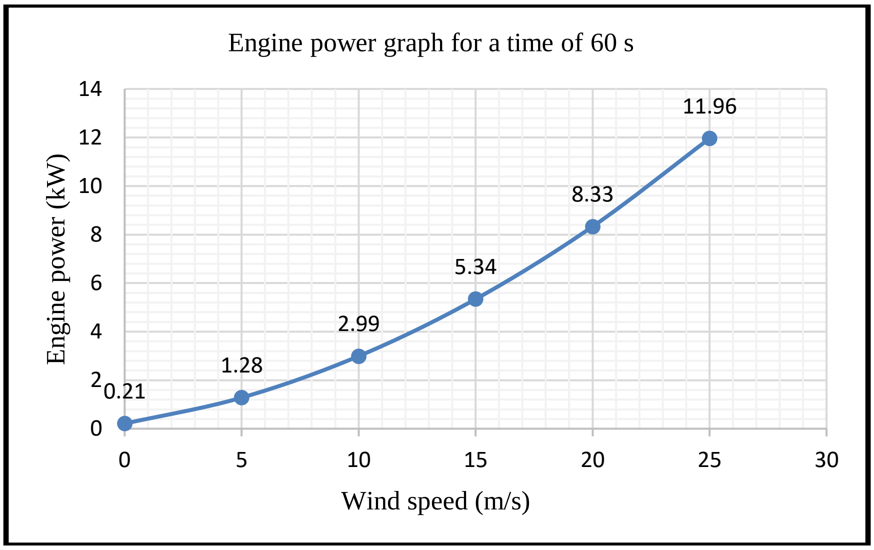
$$P = Mm \cdot \omega \text{ (kW)} \quad (13)$$

P = engine power (kW);
Mm = torque (kNm);
ω = angular velocity (rad/s).

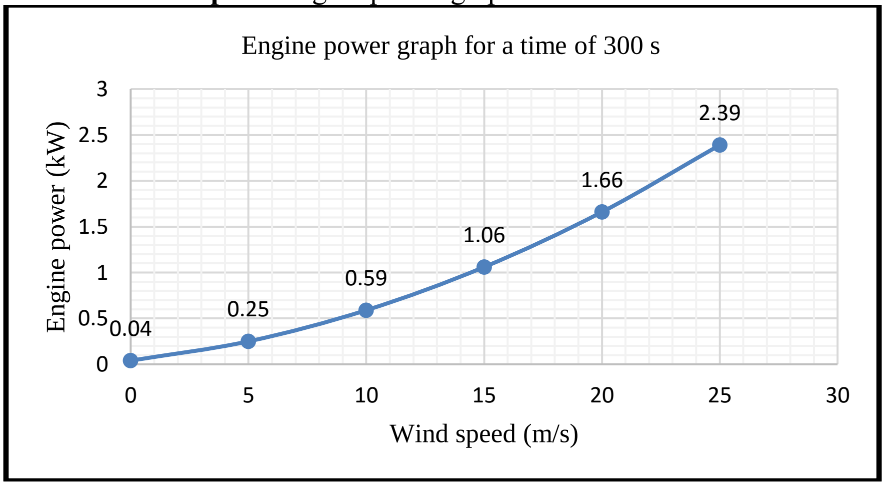
The angular velocity is calculated for a maximum bracing angle of 35^0 (0,6 rad) and for a minimum time of 60 s (**Graph 1**) and a maximum time of 300 s (**Graph 2**).

Table 5. Engine power calculation

No.	Torque (kNm)	Minimum angular velocity (rad/s)	Maximum angular velocity (rad/s)	Power 1 (kW) (t = 60s)	Power 2 (kW) (t=300s)
1	21,36	0,01	0,002	0,21	0,04
2	128,16	0,01	0,002	1,28	0,25
3	299,04	0,01	0,002	2,99	0,59
4	534	0,01	0,002	5,34	1,06
5	833,04	0,01	0,002	8,33	1,66
6	1196,16	0,01	0,002	11,96	2,39



Graph 1. Engine power graph for a time of 60 s



Graph 2. Engine power graph for a time of 300 s

3.6. TS Mircea Diesel – Generators

The 3 Diesel-generators supply the electric motors installed on the ship, the lighting network and other consumers. Their characteristics are presented in **Table 6**.

Table 6. The Diesel generators characteristics [2]

Type	D 2866 E – DEMP
Number	3
Nominal apparent power	132,5 KVA
Nominal regime power	106 KW
Frequency	50 Hz
Power factor	0,8
Nominal voltage	3 x 400 V
Nominal speed	1500 rpm

The four-stroke diesel engine with natural air intake for combustion and water cooling from the internal cooling circuit characteristics are presented in **Table 7**.

Table 7 – The Diesel engine characteristics [2]

Type	MAN D 2866 E
Bore / stroke	128/155 mm
Power	125 KW/170 CP
Speed	1500 rpm
Power for seawater cooling pump	1 KW/1,36 CP
Overload	10 %
Number of cylinders	6
Fuel used	Diesel fuel

The Mazda - Westerbake diesel emergency generator has a power of 25 KVA. It starts automatically when there is no voltage in the main distribution panel. It is launched pneumatically from specially compressed air cylinders. The engine is powered by diesel fuel from a tank with sufficient capacity for 18 hours of operation. The engine is cooled by: fresh water circuit or external air circuit. Diesel Generators are equipped with regulators that ensure the parallel operation of the three DGs over a long period of time.

To provide the ship with electricity in various navigation regimes the D.G.s operate as in **Table 8**.

Table 8. Navigation regimes of DG [2]

At berth	2 x 132,5 kVA
At anchor	2 x 132,5 kVA
Voyage	2 x 132,5 kVA
Maneuver	2 x 132,5 kVA
Emergency	2 x 132,5 kVA

The ship is equipped with three DGs, in any of the navigation regimes a spare one is provided.

On TS "Mircea" the following electricity distribution systems are used:

- 3 x 380 V, 50 Hz three-phase system with three insulated zero conductors, for power supply consumers (winch), equipment (kitchen) and electric radiators for compartments heating;
- 3 x 220 V, 50 Hz three-phase system with three insulated zero conductors, for normal and emergency lighting and low power installations;
- two-phase alternating system with two insulated conductors, at a voltage of 220 V, 50 Hz for the terminal circuits in the lighting installations, for the control and signaling circuits of

several installations, for the electro-radio navigation signals, radio communications, heating elements low power;
- 24 V direct current, with two insulated conductors for low emergency lighting.

The power supply from the shore is made by two connection panels, one on the port side and one on the starboard side, with a capacity of 250 A each and at a voltage of 3 x 380 V, 50 Hz. [2]

4. Conclusions

The present paper had two objectives: presenting a prototype of an automatic system for bracing the yards on board Tall Ship „Mircea” and analyzing its implementation on board the ship mentioned above.

Knowing and applying the maneuvers performed when sailing in good and bad weather has emphasized the importance of performing these activities in complete safety. Compliance of safety measures, knowledge of procedures and staff training play an extremely important role in sailing in optimal conditions. In order to reduce the risks of working aloft and to facilitate specific maneuvers, it is necessary to modernize the mast and rigging of the ship.

Through the automatic bracing system "Auto Sailing NS Mircea" the mast of the ship can be braced efficiently and in a short time by the officer of the watch from the navigation command. The system offers a favorable and efficient solution, without bringing major changes to the image and structure of the ship, integrating the Romanian tall ship in the modern era. Entering in the described application the input data (ship’s course and speed and the apparent wind), it calculates the real wind data and the bracing angle of the square sails. The implementation of this system would reduce the number of people involved in the activity of orienting the yards from 47 (for each mast) to 15.

The mechanical operation of the yards is performed by a motor positioned under each one. Depending on the desired bracing time, the motor can have a minimum power of 15 kW (t = 60 s) or 6 kW (t = 300 s). For the simultaneous operation of the 10 yards, the motors would develop a total power of 150 kW or 60 kW, which affects the power consumers and machines at maximum capacity of the motors.

In conclusion, the optimization and modernization of the Tall Ship „Mircea” mast and rigging is necessary and would bring several advantages. The system would also provide a favorable solution, without making major changes to the ship's image, by looking for components that integrate into its image.

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