Design Development of a Rigid-Wing Sail

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Abstract— At present, the ocean suffers greatly as a result of ever-growing population and disasters occur all over the world. A manoeuvrable ocean exploring monitoring system has been a state of the art subject for several years. The advancements in the field can be used in several market sectors and developed overtime. This system can be used for research and development purposes. Monitoring the oceans while maintaining the desired energy efficiency measures will be the main goal. This paper presents the development of an innovative rigid-wing for a sailboat likely to sail the oceans and capture data without human interaction. The product will be marketed on several platforms to be used widely in several industries. Many technical aspects still have to be studied and developed, especially regarding the boat that will be subjected to adverse climate conditions in unmanned areas, reducing the human assistance if damage occurs.

Keywords— aerodynamics, autonomous boat, structural, rigid-wing sail

I. Introduction

This proposition for a robotic sailing is not the first of its kind at the School of Engineering of the Polytechnic of Porto. Autonomous sailboats are gaining growing importance for their potential to maintain a continuous and unassisted operation at the sea surface for long periods of time [1]. The notion is to develop an efficient energy source of locomotion, with controllable parameters to effectively manoeuvre in unattended manner.

It is important to highlight that maritime monitoring field is of notable importance because the oceans (which covers 71% of the Earth's surface and contains 97% of the planet's water [2]) are presently threatened by sustainability complications. Solutions must be expanded and unassisted sailboats might play a decisive role in solving this problem. The ocean's eco-efficiency is yet to be controlled due to the vastness, therefore the multipurpose solutions a sailboat can offer is a compliment to future generations.

The proposed solution for a sustainable source of controllable locomotion has been intensely researched and developed in find an innovative concept that is capable of adapting and assisting the environment. Bearing the requirements and pre-requisite results from previous projects in mind the objective of this project is to develop a *rigid-wing sail: which can be later installed and controlled in a final autonomous sailboat*. The product will also be produced for self-assembly due to the scale of the components and the difficulty of transportation.

Research on the market of ocean monitoring systems has revealed that this is not relatively unique but designs vary indefinitely and innovative products are produced on almost every occasion. The main researched focus of this project is to integrate floatation of a hull body, adapting it to rigid-wing sail and applying controllable variables to optimise manoeuvring actions. These focus points have been addressed on the market although our project and prototype will fill new design modifications from relatable products on the market.

The paper is organized in the following sections. Beginning with Section II, which presents the primary adjustments for the boats and related projects, previously developed. In addition, Section III extensively introduces principle calculations to justify the designs expectation and from this the adopted architecture is produced in IV. The used components and fabrication process of the end product are situated on Section V. In the penultimate Section VI, the experimental evaluation of the design mechanism concept is tasked on the final design. Finally, Section VII concludes the paper, discussing the paper in regards to the results obtained and defining future developments.

II. State of the Art

The research area of boats is an intensive field with centauries of concepts that are continually developed and becoming innovative overtime. The knowledge of these continuous advancements and historical concepts must be comprehended to develop a suitable product of required characteristics. Since our goal is subject to only a rigid-wing sail design the implications of hull installations must be addressed. The hull selection implies a limitation to the sail therefore is a vital research area to achieve a reputable design.

A. Vessel Preference

The hull is the watertight exterior of a nautical vessel which

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structure is varied dependent on the operation and classification. These hulls vary structurally and traditionally are mono-hulls, but multi-hull concepts are increasing in popularity as technology advances. The stability variations that contrasting hull designs offer can considerable advantages and disadvantages to vessels depending on the operation location and use. The principles of buoyancy stated by Archimedes indicate, that the volume of the displacement of fluid is equal to the volume of the boat surface volume, which is submerged in the fluid. This also indicates the identical weight in both fluid and boat [3]. These principles signify the hulls ability of floatation due to surface area and differentials in density values. The hull selection process allowed for a variety of resilient possible designs to be explored and elaborated. Initially the Laser and SKUD18, appear to be viable contenders as both credible features.

a) Laser

Every Laser in the world is identical. The boat is a challenging boat that rewards athleticism, subtle steering and trimming techniques as well as tactical excellence [4].

b) SKUD18

SKUD18 has been designed from a performance basis, to offer scintillating, crisp and snappy response to sailors regardless of their mobility [5].

B. *Related Work*

Currently autonomous sailing is not newly discovered notion to the nautical exploration market nor as previously stated is a first for the School of Engineering of the Polytechnic of Porto. In 2007, FASt [6] autonomous sailboat was designed and implemented, focusing on participating in international competitions. The robotic sailboat followed the identical process in fabricating a lightweight kayak, using carbon fibre honeycomb sandwich hull with epoxy resin and plywood reinforced core. Although FASt developed and administered an award-winning product, it lacks crucial consideration rigid-wing sail developments. Therefore other successful projects must be analysed that show a sustained locomotion for rigid-wing sail for accomplishing long missions in the ocean in in grim conditions.

The Saildrone [7] vehicle is a recent project known for these accomplishments, demonstrated in November 2013 with a 34-day mission from California to Hawaii. The mature Saildrone design is constructed from high strength carbon fibre, creating an extremely durable structure, which freely rotates but is directed into position from the controllable tail This design illustrates a combination of mono-hull and multi-hull features to reduce the payload and enhance the stability, however, this diminishes motion control at speed. Another multi-hull project, ASN Datarmaran [8] has correspondence with Saildrone while innovation progress has been covered in the development of a dual mode propulsion system. The system consists of a self-trimming rigid wing sail and an electrically powered propeller for tight manoeuvring and added speed. The on-demand propulsion system is currently in the testing stage although all considerations of monitoring have been addressed, with an array of communication, control and power devices onboard the vessel.

Under these related circumstances end product is focused on the autonomous sailboat although this project concerns is the rigid-wing sail as the main component of our projected study. We opted to study and analyse these innovative and growing sail types to gather understanding which of locomotion systems that guarantee higher performance and allows reduction in resistance to sustained propulsion strong enough to overcome tidal currents. While, providing an accurate but simple control modulus for a low energy consumption communication and control system.

C. *Marketing Plan*

The target group and market is broad: it is the intention to reach out ocean investigation companies, who are willing and able to invest in a sustainable, energy-saving system to navigate and collect data in supporting the oceans. Nowadays, the planet is at risk as rising oceans and food sources diminish a market has been exposed for the surveillance of the vast seas. This is the new "ocean supervision" target group. As these researchers strive to protect the environment by collecting and communicating data, they are drawn to detachment of manual use. The prospected consumers are academic – professors and scientists and professionals – who have access to advanced facilities. The possible advancements of autonomous sailing can increase ocean exploration and overall knowledge of the developing planet.

PROJECT DEVELOPMENT

III. PRINCIPLE CALCULATIONS

This section is focused on the principles in floatation proves the rigid-wings ability to ensure adverse conditions at sea. Using the Laser as our preliminary vessel Impulse moments from the centre of gravity and pressure using the Laser dimensions **Table: 1** to justify the sails capability in navigation according to the design concept, introduced in section IV. All force and moments vectors for the stability and movement of the vessel can be seen in Figure 1.

LASER Dimensions [4]	
Hull Length	4.208 m
Hull Height	0.379 m
Hull Beam	1.340 m
Volume	0.931 m^3
Rectangular Volume	5.927 m^3
Approx. Total Weight (sail, hull, keel, rudder & equipment)	225 kg

Table: 1

A. *Hydrostatics*

The buoyancy must be clarified to ensure floatability for the laser with a rigid-wing instalment. Before, these calculations can be began forces in the z-axis must be assumed to be zero, $\sum F^z = 0$, following Archimedes principles. This allows the Impulse to be a determined as it can be used in relation with area of hull, gravity and density of sea water to quantify the depth at which the hull is immersed in the water.

B. Aerodynamics

The aerodynamic principle allows the boat to manoeuvre and acts as the propulsion system. The minimum wind velocity required to drive the wing can be calculated assuming a lift coefficient value of 1.5 in *Equation 5*, although previous to this the summed lifting moments, *Equation 3* before this can be done the impulse in both parameters must be defined in *Equation 1 and 2.*

$$Impulse \cdot \cos\alpha \ \cdot \Delta D = 435.2\ Nm \tag{1}$$

$$Impulse \cdot \sin\alpha \cdot \Delta D = 490.2\ Nm \tag{2}$$

$$Lifting\ Moment = Impulse_1 + Impulse_2 = 435.2 + 490.2 = 925.4\ Nm \tag{3}$$

$$Lift = \frac{Lift\ Moment}{cos30 \cdot (h_{CG} +\ h_{CP} + h_{hull)}} = 539.9\ N \tag{4}$$

$$Velocity = \sqrt{\frac{2L}{\rho_{air} \cdot A \cdot Cl}} = 15.2\ m^2 \tag{5}$$

C. Dynamic equilibrium

The equilibrium in vessels and sails have to be achieved to a vessel from capsizing to do this wind, currents and tides are taking influences must be taken into consideration. When the boat is in motion and external forces are influencing the stability of the boat and it is preserving a point of equilibrium. The principle of creating an overall dynamic equilibrium it must be assured that the sum of all forces and moments are equal to zero to be in equilibrium, shown in *Equation 6*.

$$\sum F_x = \sum F_y = \sum F_z = \sum M_x = \sum M_y = \sum M_z = 0 \tag{6}$$

In this equation F refers to the forces in x-, y- and z-axis and M refer to the moment in the axis.

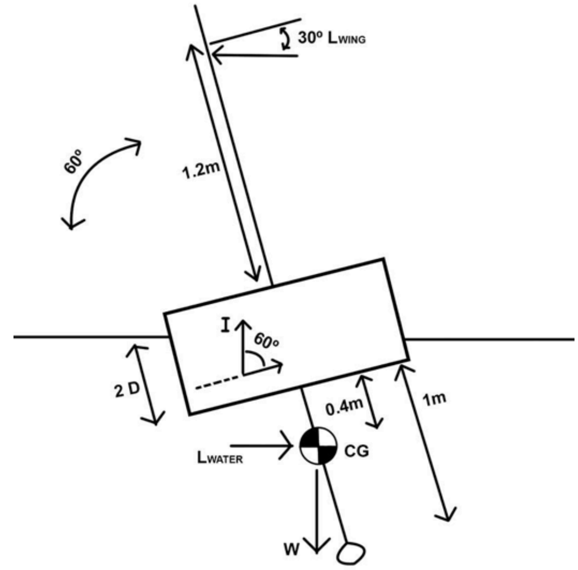

Figure 1: Stability and Movement

IV. Architecture of Developed Wing & Boat

In this section, the architecture for the boat with the rigid-wing sail feature developed for the project is introduced. The goal is to develop a wing sail that can be controlled to optimize positioning and orientation while adapting to the operation environment.

Based on the considered aerodynamic principles and assessments of existing airfoil profiled sails, a NACA 0012 airfoil was adopted for the sail as seen in Figure 2. This airfoil geometry is symmetrical and efficient in controlled easily, as the wing increases vertically these airfoils are reduced in size to reduce sail area, allowing for greater control and less weight.

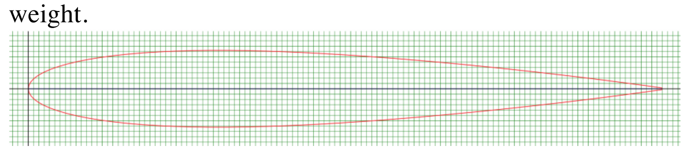

Figure 2: NACA 0012 airfoil

Similar to related projects the development, the airfoil profile is erected vertically as the profile is reduced substantially to lower the area of wing exposed to drag allowing for a greater lift. The interior structure of the rigid wing sail can be seen in Figure 3, the controllable stabiliser is also indicated in this image. Furthermore in Figure 4, the covered wing can be seen.

Figure 3: Structural interior of the sail

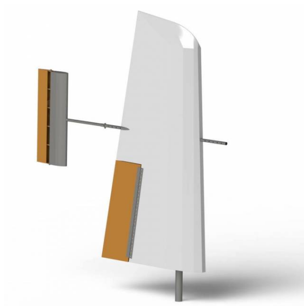

Figure 4: Rigid-wing sail

To comply with the final goal of creating a rigid-wing sail, which can be later assembled to a vessel and operate autonomously. The rigid-wing sail integrates adaptable features: the key rigid wing concept, mechanical control and sensor alterations, stabilizer modifications and adaptable vessel will be presented in section V.

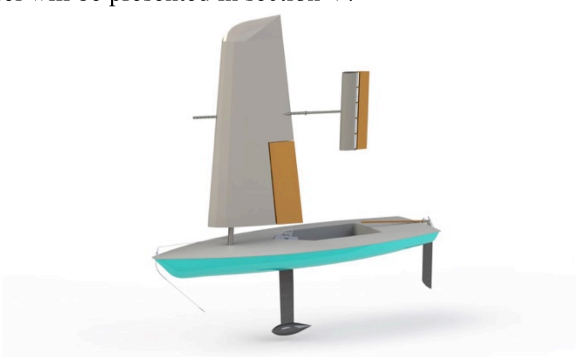

Figure 5: Final rigid-wing sailboat concept

V. Final Wing-sail Components and Implementation

This section details the components used for the realization of a final wing-sail product, which is based on the architecture described in section III. The wings skin coverage, internal structure, wing and stabilizer mechanism, hull to wing-sail configuration and electronic devices are explained.

A. Internal Structure

The structural integrity of the wing is dependant on a variety of components including: stainless steel and wooden masts, lateral supports, airfoil profiled ribs and horizontal beams.

1) Masts

a) Stainless Steel

Stainless steel 316L will be used for a segment of the mast. It will add structural stability from the hull to the wing sail. The material sourced has yield strength of 290 MPa. This is the maximum value of stress before plastic deformation begins and as the wing is allowed to move freely it is an alternating and fluctuating stress, which increases the chances of failure. A factor of safety value of 1.22 has been indicated and the probability of failure due to bending on the mast. It is vital for failure criterion by this proving the mast dimensions as a viable design aspect of the rigid wing sail.

b) Wooden Masts

The wooden masts will be situated in both the main wing and stabiliser and will take the form of an I-beam for structural stability while added flexibility is free to manoeuvre. The I-beam profile is used to calculate the moment of inertia in the structure, that allows a maximum wind pressure of 500 N on the internal structure. This allows for the minimum moment of inertia to be calculated and made viable from the bending moment calculation. The wood will be a combination of maritime plywood and treated pinewood suitable for aquatic use.

c) Lateral Union

The lateral union will be positioned in the front edge of the airfoil acting as a structural brace for the oncoming forces. It will be manufactured by treated pinewood suitable and bonded to the ribs and remaining structure with high strength polyurethane adhesive.

2) Ribs

As the ribs act as the propulsion system as the profile is developed to increase efficacy when using wind a locomotion source it also acts as part of the internal structure. The ribs profile can be previously seen in Figure 2, maritime plywood has been defined for this component. The lightweight and pliable material suits the need for the internal structural ribs as they are positioned upright and evenly on the masts.

3) Stainless Steel Connectors

The stabiliser is connected to the main wing with a stainless steel 316L beam that is connected together from M6 stainless steel bolts. The connections are positioned to act against bending and torque created by the weight and wind pressure on the stabiliser. These beams are structurally stable to handle these forces due to the identical elastic deformation as the stainless steel mast.

B. Skin Coverage

The skin coverage is the greatest exposed area to the external conditions therefore we chose marine plywood as our structural protection layer. This material is commonly used in marine applications, it is composed from selective grades and these grades create a protective, immensely strong and long lasting material. The pliable form of the plywood will allow for the material to flex around the skeleton frame while maintaining structural integrity. These sheets will be adhesively bonded as a primary fastener for the wooden structure. The selection of Sikaflex 292 polyurethane adhesive was favoured because of strong, waterproof, and suitable for exterior use and, to some extent, solvent tolerant [9]. Saving weight will be vital to in the reduction of the wing weight therefore plywood panels will be removed and replaced with epoxy coated balsa panels. These panels exposed to the epoxy resin will harden the grain and increase the rigidity while maintaining flexibility.

C. *Mechanical Mechanisms*

The control mechanisms of the wing sail consist of both the flaps actuator and the stabilizers servomotor. These instruments must transmit to a control unit, which is further stated in subsection *Electrical Devices*. The synchronization between both control variables will be done so by this control unit.

1) *Flap Control*

The control of this design parameter is achieved by an Electric Linear Actuator [10] with an encoder for positioning control. The allocated actuator is located on a central rib of the main sail and connected to the flap via a 1-metre piano hinge, which acts as a centre of rotation, turning the linear movement of the actuator into a rotation movement for the flap. In addition, the encoder will be configured to shift the stroke to a specific distance that gives 20º to the flap for each side. The actuator setup can be seen in Figure 6, the arrangement displays all the internal structural components and more importantly the actuator configuration to the flap control.

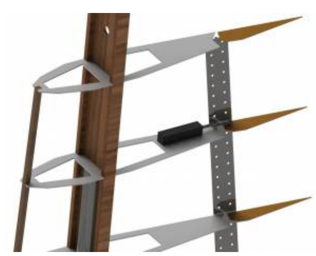

Figure 6: Actuator position on rib

2) *Stabiliser Control*

The stabiliser unlike the flap control requires less force to manoeuvre and position, therefore, a servomotor will be has been designated to perform this operation. The servomotor will be situated in the static rib and connected to a vertical shaft with two rigid cables that is fixed to a rotating rib, this will transmit the rotational torque from the servo to the stabiliser position.

D. *Mast and vessel configuration*

The connection between mast and hull body has to be accurately designed, considering all parameters of movement. The mast must be able to rotate freely around an angle of 360 degrees, although this must be controlled and limited to prevent destabilization of the rigid-wing sail within the hull. The proposed solution previously stated is to install flange bearings of adequate dimensions to accommodate the 70 mm diameter mast this will stabilize the mast in the body of the hull. These bearings will be lubricated to reduce wear on both the mast and bearing housings [11].

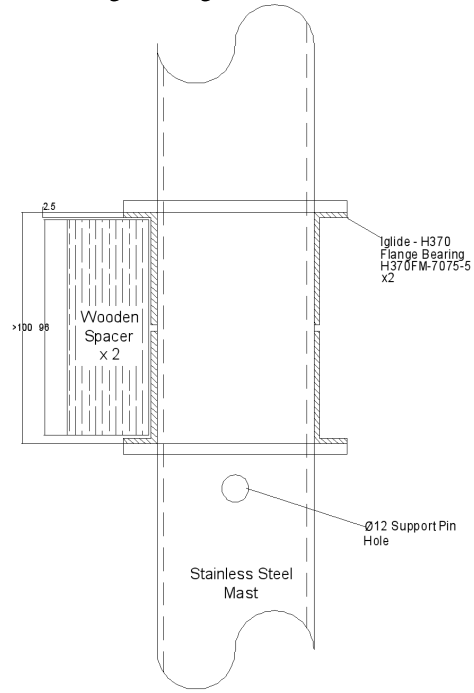

Figure_: Mast rotation mechanism

E. *Electronic Devices*

It is paramount that the configuration of electrical appliances is predetermined due to our proposed manufacturing process. The system will be enclosed in the skin of the wing this causes great difficulty to renovate the system within the sail. The prospected components include: battery, navigation lights, actuator, wind sensor and servomotor. The implementation of these electrical devices must be accommodated in the design of the wing sail in terms of positioning and connections. Internal wiring will make this connection by PVC duct pathways although the hull will contain the control unit and deliver commands via Wi-Fi or Bluetooth. These parameters will be customisable by the client.

VI. Experimental Tests and Results

A series of tests was required to make the alternative prototype and implemented rigid-wing sail is working as expected. After testing of the wings externally waterproof and the mechanisms motion is operational, the experimental evaluation of the wing-sail lift value will be presented and discussed.

A. *Waterproofing*

The first test that will be conducted regarding the water resilience, there are various possible defective areas on the wing that may be inclined to fail this tests. It will likely be a small gap between glued components that cause water entering the internal wing sail. Taking this into consideration and the fact that splash water is foreseen to enter the sail at the connection point of main sail and flap, holes are made at the bottom of the sail to discharge the water. Furthermore, precautions are made to protect electrical devices from incoming water, either by choosing waterproof devices, or by covering the device with protection measures.

B. Wing and stabiliser motion

The motion of jib and flap installation process and test is completed before the final material will cover the sail. The defined target is a movement of ± 20° from 0°, the actuator will position the jib, which is located in the main wing. The actuator is positioned and fixed on a central rib to increase the area of movement this test will be complete by calculating the total radius moved in both directions of the flap control. The stabiliser will need to complete this motion in almost the same time as the actuator, thus a degree of synchronisation must be completed and to be monitored upon its correct functioning.

The results indicate that both jib and stabiliser move as expected in dry condition. To improve the undulating movement of the jib, the actuator will be extended to enhance a larger angle, which can be manually changed by replacing the rod connected to the actuator and jib. It needs to be tested if this motion of 20 degree's of the jib creates enough movement at the right angle to counteract the wind speed when in operation.

C. Lift test

The lift test can be performed either in a wind tunnel or the outdoor environment in the best conditions. For both conditions the testing plan will change drastically. Besides not having access to a sufficient wind tunnel, the test must occur outdoors. The wing will be positioned on a fabricated steel bracket, which is limitedly tied down and weighted to prevent collapse during the lift of the wing. The test must be carried out in optimal wind conditions to produce the efficient lift on the wing without flipping and damaging the wing. The support bracket will gradually be reduced in weight until an upwards-lifting force can be seen. The target is to acquire its maximum weighted lift. This value will be used to meet the predetermined calculations and justify our decisions in building the wing in this form.

VII. Conclusion and Future Work

In the beginning of this project, detailed knowledge about the research field has been gathered, although halfway during the course the attention had been changed becoming concisely fixed on a new goal of a rigid-wing sail. Although not a new topic, the design for a rigid sail was recently discovered by our team thus vast amounts of research. This concerned the competitors and laws of physics that served as groundwork for the product development and confirmed the innovative individuality for the client. Our group members have developed in each individual's respective area of study, project management and ecological rationality. The experience focus was partially on the functionality as a team and how we collaborated, tasked and controlled while being culturally and academically challenged.

Following this project, we have categorized both short-term and long-term goals that will see provide a fully furnished product to the client. The initial short-term goal will be to establish a wing-sail with quality components and completion of all functional tests with satisfactory results. At this time no initially proposed requirements where practically fulfilled, only the theoretical concepts have been produced for the project. The final short-term goal will be to reduce the amount of toxic and harmful materials, holding paramount the enhancement of safety for the user and environment.

Although the initial purpose has been obstructed we have still produced quality models and concepts for the long-term development of an autonomous sailboat. This long-term goal will include the integration of initiating a suitable platform while considering sustainable measures of energy generation. In addition, the user manual can be elaborated further to allow users to assemble and programmable route manager as the innovative product can be characterized especially to individual customers.as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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References

[1] José Carlos Alves, Nuno Alexander Cruz. (2014). METASail – A Tool for Planning, Supervision and Analysis of Robotic Sailboat Missions. In: Fearghal Morgan, Dermot Tynan *Robotic Sailing 2013*. Bucher: Springer.

[2] NOAA. (2014). *Ocean*. Available: http://www.noaa.gov/ocean.html. Last accessed 2th June 2015.

[3] Clifford A. Pickover (2008). *Archimedes to Hawking: Laws of Science and the Great Minds Behind Them*. Oxford: Oxford University.

[4] Laser. (2015). *Laser Dimensions*. Available: http://shopeu.laserperformance.com/laser/. Last accessed 7th June 2015.

[5] SKUD18. *SKUD 18*. Available: http://www.skud.org/?Page=18384. Last accessed 4th June 2015.

[6] FEUP. (2008). *FASt Autonomous Sailboat*. Available: http://paginas.fe.up.pt/~jca/fast/. Last accessed 1th June 2015.

[7] Saildrone. (2015). *Saildrone Vehicle*. Available: http://www.saildrone.com/index.php/technology. Last accessed 8th June 2015.

[8] Autonomous Marine Systems. (2013). *Datamaran Datasheet*. Available: http://www.automarinesys.com/wp-content/uploads/2014/05/Datamaran_DataSheet.pdf. Last accessed 8th June 2015.

[9] Sikaflex. (2002). *Sikaflex 292 Datasheet*. Available: www.pinmar.com/docs/Productos%20-%20TDS%20-%20Fichas%20Tecnicas/en/Sika/Sikaflex/Sikaflex-292.pdf. Last accessed 10th June 2015.

[10] Festo. (2015). *Electric cylinders EPCO Datasheet*. Available: http://www.festo.com/cat/pt_pt/data/doc_engb/PDF/EN/EPCO_EN.PDF. Last accessed 6th June 2015.

[11] IGUS. (2012). *IGUS Bearing Datasheet*. Available: http://www.igus.com/_Product_Files/Download/pdf/BCC_INT_iglidur.pdf. Last accessed 10th June 2015.