Peruagus - a Transatlantic Autonomous Surface Vessel for the Microtransat Challenge

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Abstract

The Microtransat Challenge is a (friendly) transatlantic, unmanned boat race, aimed to stimulate the development of autonomous boats. Since the first transatlantic Microtransat race in 2010 there have been over 20 entries and no successful crossings in all classes (sailing, non sailing), divisions (autonomous, unmanned) and routes (East to West, West to East). This paper presents the design and development of Peruagus, the University of Southampton 2018 Microtransat transatlantic autonomous surface vessel entry. Peruagus, meaning Globetrotter in Latin, was developed as part of a final year group design project at the University of Southampton. The design of the vessel (a mono-hull, self righting, solar powered vessel) including the system architecture, hull design, propulsion, steering, power and control systems and experimental results from a series of self propulsion tests, sea-keeping tests and autonomous operations are presented. The results demonstrate that the vessel is able to self right, propel itself with low power and operate autonomously over a range of conditions. In addition, performance predictions are presented and based on a fault tree analysis the vessel is currently predicted to have a 60% chance of success. The vessel is planned to be launched in the summer of 2018.

1 Introduction

1.1 The Microtransat Competition

The Microtransat Challenge, a transatlantic unmanned boat race (Figure 1), aims to stimulate the development of autonomous boats through friendly competition. The competition, first conceived by Mark Neal (Aberystwyth University) and Yves Briere (ISAE) in 2005, was first attempted in 2010 by Pita from Aberystwyth University (Microtransat, 2018a). Since the first transatlantic Microtransat race in 2010 there have been over 20 entries. Although the challenge is simple; autonomously travel either between Europe and the Caribbean (east to west route) or North America and Ireland (west to east route) in the fastest possible time, as of writing there have been no successful crossings in all classes (sailing/non sailing), divisions (autonomous/unmanned) and routes (East to West/West to East).

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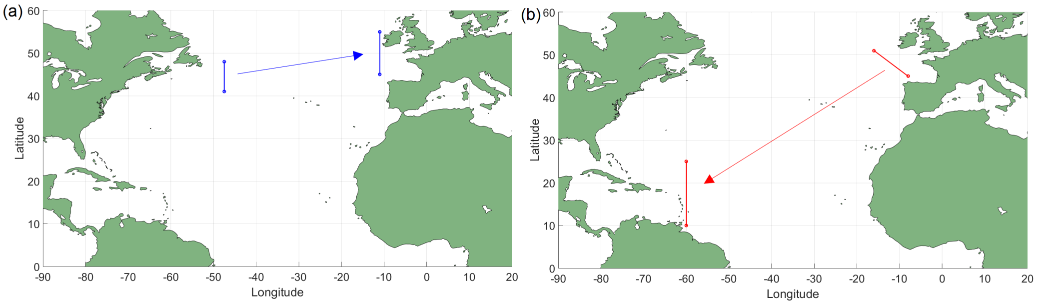

Figure 1: The Microtransat Challenge ((a) West to East route (blue), (b) East to West route (red)).

A breakdown of entries by class and division and failures is given in Table 1. The majority of entries are in the sailing class (using wind as their propulsion power) and entered in the autonomous division. Reviewing the known failures, the technical failures primarily relate to issues of reliability - surviving in the harsh environment for a prolonged period of time. While the non-technical failures relate to route hazards - fishing grounds, shipping lanes and the Sargasso Sea (an ocean gyre off the coast of northern America and the Caribbean characterised by brown seaweed, which creates obstacles for the vessel).

	Sailing Class Only wind power can be used for propulsion, overall length (LOA) restricted to a maximum of 2.4m	**Non-Sailing class** Any type of propulsion can be used, overall length (LOA) restricted to a maximum of 2.4m
Autonomous (Division) No interaction between the team and the vessel, only publicly available data can be received by the vessel (i.e. no waypoint changes	Pinta, Snoopy Sloop 10, Snoopy Sloop 11, Breizh Tigress, Opentransat *Erwan 1*, *Aboat Time*, *Trawler Bait*, *Phil's Boat*, Breizh Spirit, Breizh Spirit DCNS, Snoopy Sloop 8, Snoopy Sloop 9, That'll do	That'll do two (Epsom College Entry)
Unmanned (Division) Data can be sent to the boat, including course changes	Gortobot V2, *SB-wave*	

Table 1: Summary of Microtransat classes, divisions and failures by vessel name. (*Italics denotes a non-technical failure e.g., picked up by fishing vessel*, Underline denotes technical failure e.g., position report failure, unmarked denotes unknown or sailed into land). Data from (Microtransat, 2018b)

Furthermore, considering vessel size and performance (time sailed and distance covered) there are no apparent trends, Figure 2. Neither is there a clear improvement in performance over the years the competition has been running, although this can be attributed to the small dataset and difficulty of the challenge. In this regard it is hoped this paper will provide a valuable insight for new teams and entires in the Microtransat.

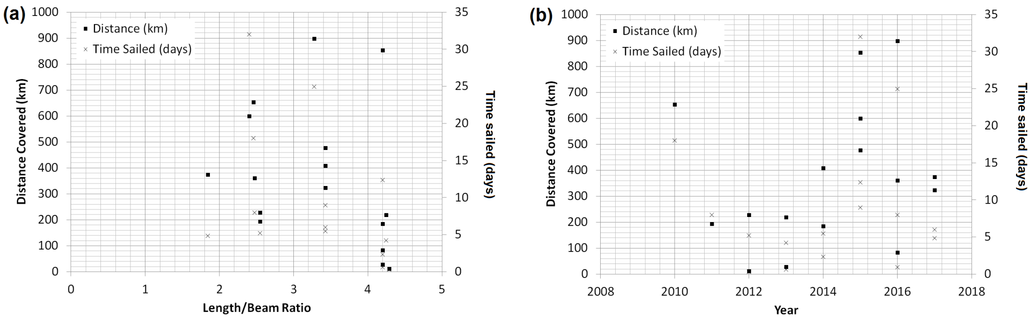

Figure 2: Comparisons of previous Mircotransat Entries ((a) Length/beam ratio versus distance and time sailed (b) Year versus distance and time sailed)

1.2 The Peruagus Project

Peruagus, meaning Globetrotter in Latin, is the University of Southampton 2018 Microtransat transatlantic autonomous surface vessel entry. The Peruagus project was a final year engineering group design project at the University of Southampton. The group design projects (GDPs) at the University of Southampton (University of Southampton, 2018) aim to provide students with the opportunity to demonstrate their knowledge and skills, gained during their degree, to a 'grand' engineering design challenge. In this regard competitions can be used to great effect, as reported by (Telegraph, 2016) and exemplified by Xprize (Xprize, 2018), Eurobot (Eurobot, 2018), formula student (IMechE, 2018) and maritime engineering related competitions including the World Robotic Sailing Championships (WRSC, 2018) and the International HydroContest(Hydros Foundation, 2018). In particular, the Microtransat competition has provided a multi-faceted, challenging, motivational, open-ended engineering problem. This has enabled students to demonstrate and integrate knowledge acquired from across their programs but also provided the opportunity to interact and contribute to an international community.

The aim of the Peruagus project is to design and develop a vessel to cross the Atlantic, as part of the Microtransat Challenge. Since the vessel is required to operate unmanned and travel for several months autonomously without maintenance and with all previous attempts unsuccessful, a failure analysis approach was used to guide the design of Peruagus, focusing on reliability (minimising the probability of system and subsystem failures to maximise the chances of success).

1.3 Contribution and Paper Structure

In this paper, the design of Peruagus, a mono-hull, self righting, solar powered vessel, is presented. The system architecture, hull design, propulsion, steering, power and control systems are detailed in Section 2, including experimental results from a series of self propulsion tests, sea-keeping tests and autonomous operations. The final vessel design, targeting the Mircotransat non-sailing class, autonomous division (with the possibility to convert to unmanned) following an east-west route, is presented in Section 3 and performance predictions are presented in Section 4.

2 Peruagus Vessel Design

2.1 System Architecture

An overview of Peruagus system architecture is given in Figure 3. The electrical system is split into a pair of redundant circuits, each comprising of a 100W solar panel made up of SunPower cells, a Victron BlueSolar MPPT charge controller, a battery bank (2 x 480Wh lithium-ion batteries), control relays and a step down voltage converter. The solar/battery bank (12-14V) provides power to the drive motors, steering actuators, the navigation light and the bilge pump. A step-down voltage converter (also powered from the solar/battery bank) then provides a regulated 5.6V supply for the on-board control systems, including;

1. The navigation controller (Pixhawk), which acts as the navigation controller, and manages the power distribution and makes decisions based upon the condition monitoring sensors
2. The satellite modem (RockBLOCK+) which transmits telemetry and location data every 6 hours using the Iridium network
3. The microcontroller (Teensy 3.5), which provides data acquisition, processing, logging and (I2C) communication with the navigation controller.

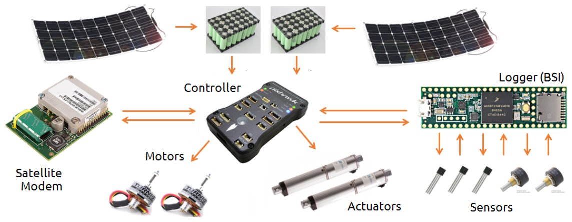

Figure 3: Overview of Peruagus Architecture

2.2 Hull Design

To house all the systems a mono-hull, self righting, solar powered vessel with passive keel cooling was developed. The hullform, as shown in Figure 4, was made of a double skinned foam core (Celotex PIR wall insulation foam, milled from a foam block using a CNC machine) with E-glass ($290g/m^2$ with $100g/m^2$ finish) infused with EL2 epoxy resin. The foam thickness has a total volume of approximately 100kg displacement. This ensures that if there is water ingress and the compartment becomes flooded the vessel will maintain positive buoyancy. The propeller shafts were also angled at 15 degrees, to ensure the stern tubes ends were above the waterline such that in the event of a seal failure water would not flood the boat.

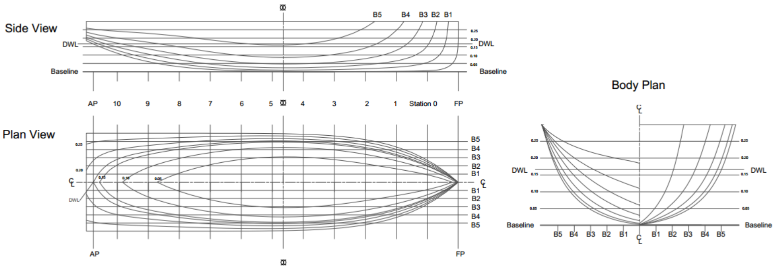

Figure 4: Peruagus hullform

2.2.1 Stability

Given the slender form, solar panel requirements and potentially severe sea-states, Peruagus was designed to be self righting and remain self righting in the event of damage and flooding. This was achieved with a keel, watertight compartments and an asymmetric superstructure. The keel (NACA0010 section) was made from PET plastic, housing 16kg of lead ingots constructed around an aluminum frame. The GZ curves for the intact vessel and damaged vessel are given in Figure 5.

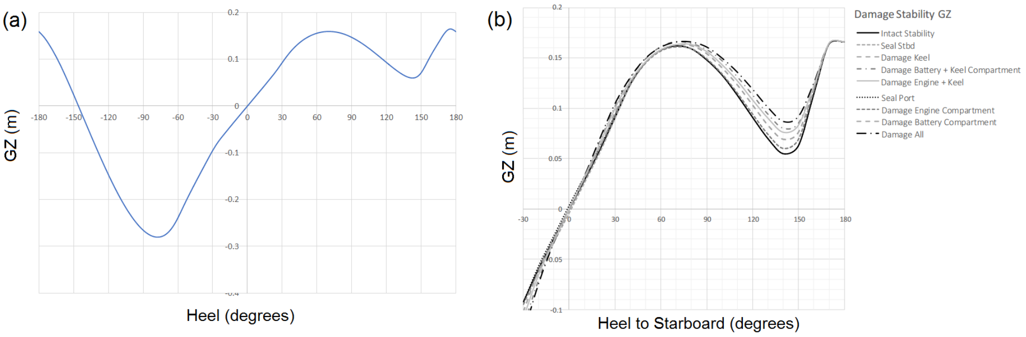

Figure 5: Peruagus GZ stability curves ((a) Intact (b) Damaged)

2.2.2 Seakeeping

To assess the seakeeping performance of Peruagus a series of observational experiments were performed in the University of Southampton towing tank, including a worse case scenario when the wave length was equal to the LBP, Figure 6. As the vessel is unmanned and the limiting factor for seakeeping performance is the tolerance of the electronics, this approach which does not necessitate the testing of every possible sea-state that may be encountered, significantly reduced the number of tests required. The results, Figure 6, show that the accelerations experienced by the vessel are within tolerance of all electrical systems. For example, the most sensitive system onboard, the GPS, is rated to withstand up to 4G acceleration. While the wave height is limited in the towing tank, these tests provided confidence in the seakeeping performance of the vessel.

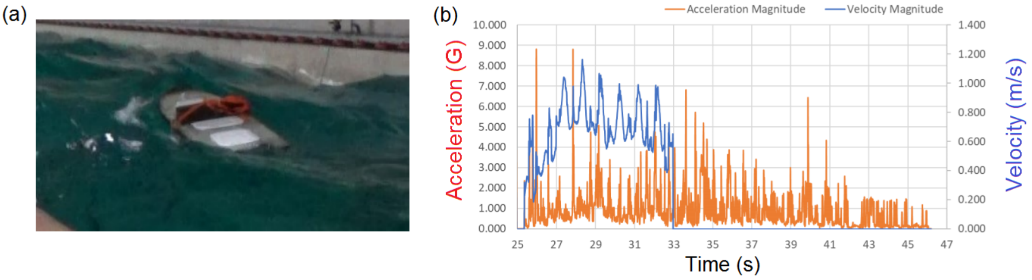

Figure 6: Peruagus Seakeeping ((a) Image of test, (b) Heave acceleration and velocity recorded using an IMU)

2.3 Propulsion System

Propulsion was achieved with two inwards rotating propellers, providing (if necessary) differential thrust for steering in the event of a rudder malfunction. To establish the resistance and estimate the required propulsion power for the hull, the viscous resistance was estimated using the ITTC 1957 correlation line (Molland et al., 2017) with a form factor identified from CFD simulations (using ANSYS Fluent) and the wave resistance coefficients were determined using Maxsurf resistance Slender Body Analysis (assuming Peruagus can be regarded as a fully displacement traditionally shaped vessel). The results are shown in Figure 7. The power estimates were made assuming the following efficiencies; Propeller Angle Efficiency 96.59%, Propeller Efficiency 60%, Transmission Efficiency 95% and a Weather and Fouling Margin 30%. Based on the results, a 140W design specification was considered (enabling a nominal 45-55W 'cruise' operation and 'sprint' ability to maintain progress in adverse conditions or in the event of an engine, belt, shaft or propeller failure).

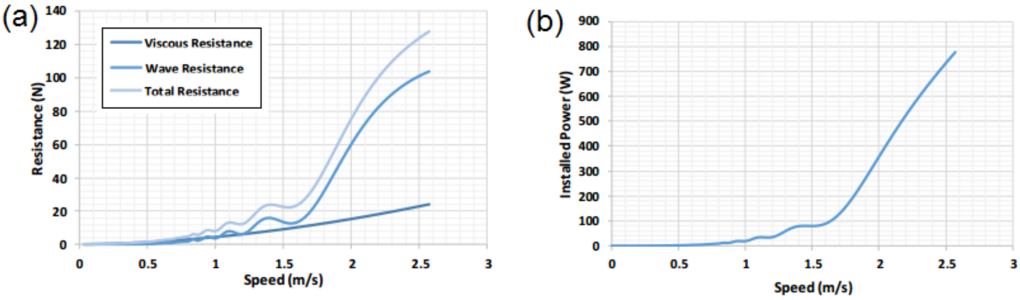

Figure 7: Estimated resistance (a) and power (b) over a range of speeds

2.3.1 Drive System

A pair of brushless hobby-grade (Turnigy DST-700kv, 12V) motors were selected for propulsion. With a nominal no load speed of 8,400rpm (12V), a 1:4.4 geared belt drive system was implemented to provide the propeller design speed of 650-800rpm. To check the longevity of the motor and controller, the motor was run for over 3000 hours, with an applied load (an airscrew), cycling between cruise (20-40% throttle) and sprint throttle levels to provide a representative load cycle. Although, an increase in bearing noise was noted, the motor and controller ran without fault with no notable increase in power consumption, providing confidence in the selected drive system.

2.3.2 Propeller Selection

The propeller selection was based on an experimental investigation of 4, 5 and 6 bladed Wageningen B-series propellers (Van Lammeren et al., 1969) (readily available brass model boat propellers designed to operate at 750 rpm at 1.5knots). The 4, 5 and 6 bladed propellers were 3D printed (for the experiments) in high density ABS and vessel speed, power (current drawn) and rpm, over a range of throttle settings, in the University of Southampton Boldrewood towing tank, were recorded, Figure 8. Based on the results, Figure 9, the five bladed propeller was selected. The results show a slight discrepancy between the theoretical estimates (see section 2.3) where an installed power requirement of 8.07W at 1.5knots 'cruise' speed (0.77m/s, Fn0.168, 4.43N resistance, 4.58N thrust), and installed power requirement of 80.8W at 3.0knots 'sprint' speed (1.54m/s, Fn0.336, 22.18N resistance, 22.96N thrust) was calculated.

Figure 8: 3D printed propeller (design, manufacture, assembly, testing)

According to the results of the self-propulsion tests, the motors operate at approximately 40% (each) at normal cruise speed, drawing a total of 48W. One motor was found to push the vessel at a maximum speed of 2 knots at full applied power (drawing approximately 80W). While both motors operating at full applied power, produced a speed of just below 3 knots (drawing 160W total). Based on the results the boat is intended to be operated for the majority of journey at 'cruise' power (45-55W continuous input), with the ability to 'Sprint' to maintain progress when encountering tidal streams, current, or heavy weather.

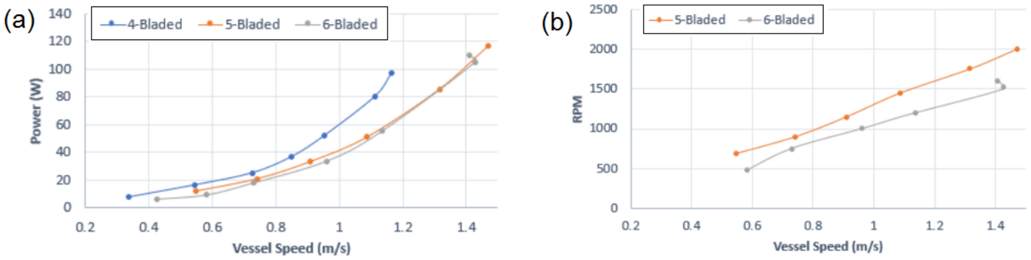

Figure 9: Propeller test results ((a) Power (b) RPM)

2.4 Steering System

To steer the vessel a doubly redundant system was developed with two linearly actuated control surfaces (rudders) and two inwards rotating propellers (if necessary in the event of rudder failure) providing differential thrust. The rudders were designed to manoeuvre the vessel and, in case of a propulsion failure, counteract the moment produced by a single, one-sided propeller. This approach was adopted, based on advice provided by ASV Global Ltd and on the main causes of failure of small ocean going craft; failed rudder servos (e.g., from salt water seizing the electronics or strong forces damaging the actuator) (Microtransat, 2018b) and complete rudder loss (Seacharger, 2018). In addition, linear actuators also have the added advantage that they can hold their position without the need for power.

2.5 System Power

To power Peruagus an asymmetric superstructure solar battery charging system was implemented. Since the transat is in the northern hemisphere and one way - east to west, the asymmetric superstructure maximises the incident solar energy and additionally aids in self righting (with a tendency to right itself to starboard). In total two 100W (18V) Mono-crystalline solar panels ($\eta = 23.5\%$), were selected and wired in parallel, with each panel charging two Lithium Ion batteries (12V, 3S 40Ah) (with a Victron solar controller and built-in profile for Lithium Ion cells; lower voltage cutoff of $\approx$ 8.5V and a maximum voltage of 12.6V).

2.6 System Control

The control system is based on the Ardupilot Rover, using GPS to steer the vessel between waypoints as shown in Figure 11. A major modification to the Ardupilot Rover basis firmware is the addition of the Director, which acts as a proxy between the autopilot and the physical hardware. The autopilot code sends a desired throttle and steering value to the Director. The Director, which continually monitors the vessel to detect failures, then drives the motors and rudders accordingly (given the system status) following prescribed rules. In addition, the Director also monitors longer term navigational performance e.g., IMU data to detect the severity of boat motions, ability to maintain headway, capsize events and system failures. This data can be reported to the shore base and actions including; adding/changing waypoints, overriding autopilot decisions on failure, change the data sent in the status message, request a full diagnostic to be sent (multiple messages), manually set throttle or steering angles, switch to drift/loiter mode and conduct a reverse 360, can be taken. Meaning that, in the event of an unforeseen failure there is the possibility to convert to the unmanned division. Although, the 'rules' or thresholds remain to be finalised, initial tests have been conducted to provide confidence in the control, with Peruagus run autonomously for an hour tracking between waypoints in a local lake.

3 Final Peruagus Design

The final Peruagus design is presented in Figure 10 and Table 2.

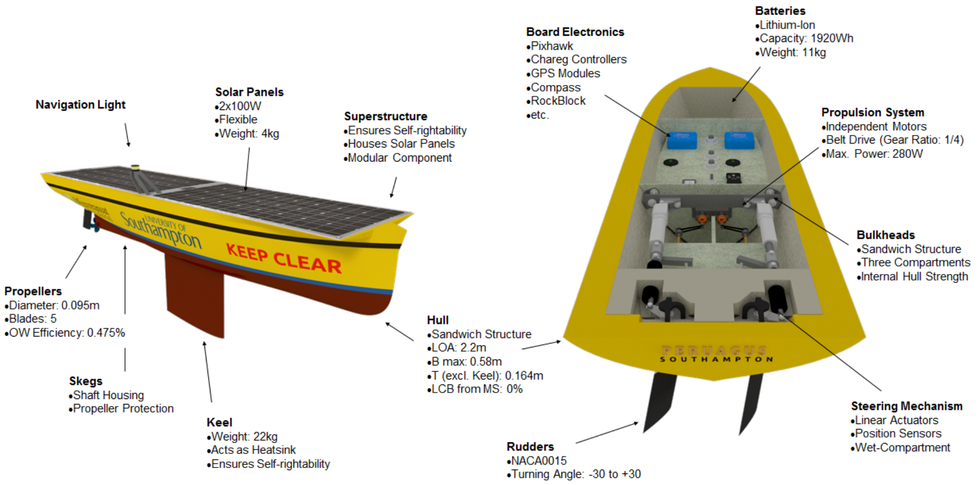

Figure 10: Peruagus General Arrangment

HULL PARAMETERS	
Length (LOA, LWL)	2.2m, 2.158m
Beam (WL, Max)	0.475m, 0.58m
Draft at FP (at AP)	0.162m (0.14m)
Displacement	80.4kg
Block Coefficient, CB	0.454
LCB, LCF, GMt, Trim	1.16m, 1.071m, 0.167m, -0.021m
PROPULSION SYSTEM	
Propellers	2× 5-bladed Raboesch M5 propellers, 110mm diameter
Propeller drive	2× Model DST-700, 140W, 700RPM/volt, brushless
STEERING SYSTEM	
Rudder Shape	NACA0015 (widened near the stock)
Rudder Material	Acrylonitrile Butadiene Styrene (ABS) and Epoxy
Rudder Area	$0.014m^2$
Mean Chord, Span, Sweep	0.10m, 0.14m, 20^o
Aspect Ratio	1.4
SYSTEM POWER	
Solar Panels	2× 100W (18V), Monocrystalline, 1050mm x 540mm x 2.5mm, $\eta = 23.5\%$
Batteries	4× 480WH, 12V (Nominal) Lithium Ion (3S 40Ah), rated discharge 40A, rated charge 10A, 12.50kg (total)
CONTROL SYSTEM	
Navigation Controller	Pixhawk
Satellite Modem	RockBLOCK
Microcontroller	Teensy 3.5

Table 2: Peruagus particulars

4 The Peruagus Entry

4.1 Vessel Route

Peruagus is planned to be entered into the Mircotransat non-sailing class, autonomous division (with the possibility to convert to unmanned in the event of a required interaction) following an east-west route. To minimise the probability of failure the planned route (as much as practically possible) avoids fishing grounds, shipping lanes and the Sargasso Sea, Figure 11. Although, the east-west route is longer and arguably more challenging, with a 91% probability that one hurricane will be encountered in the course of the transit (NOAA, 2018), it is practical for a UK team and the average wind and waves directions are favourable.

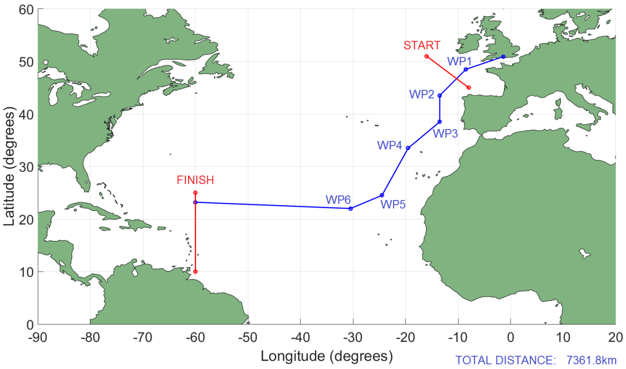

Figure 11: Peruagus Route

4.2 Estimated Duration

Using the Haversine formula (Mwemezi and Huang, 2011) to calculate the distances between the planned waypoints (latitude,longitude) and assuming a constant 'cruise' speed of 1.5knots (55W), the total journey is expected to take around 16 weeks, Table 3. Although neglecting the influence of any current, wind and waves, these estimates will enable a comparison with the actual performance and potentially highlight performance issues on route.

Waypoints	Latitude (N)	Longitude (W)	Distance (km)	Propulsion Energy (MJ)	Duration (Weeks)
Southampton	50.91^o	1.40^o			
Waypoint 1	48.50^o	8.50^o	565.24	40.3746	1.2138
Waypoint 2	43.50^o	13.50^o	667.05	47.6461	1.4324
Waypoint 3	38.50^o	13.50^o	555.97	39.7125	1.1939
Waypoint 4	33.50^o	19.50^o	762.88	54.4911	1.6381
Waypoint 5	24.50^o	24.50^o	1103.31	78.8080	2.3692
Waypoint 6	22.00^o	30.50^o	667.76	47.6972	1.4339
Finish line	23.20^o	60.00^o	3039.62	217.1155	6.5270
		TOTALS	7361.83	525.8451	15.8082

Table 3: Peruagus estimates (assuming a constant cruise speed of 1.5knots at 55W)

4.3 Probability of Success

To determine the probability of success a deductive failure analysis in the form of a fault tree was conducted, as illustrated in Figure 12. Over 200 identified events (each representing a possible cause of failure of one of the vessels systems) were identified and probabilities of failure assigned. The probabilities were based on the test results, available literature, however, some probabilities were difficult to quantify and estimates were made. The final analysis estimated the probability of success at approximately 60%.

Given the history of the competition this figure seems reasonable, however it is important to note that there is a degree of uncertainty associated with this number. For example, the largest contribution to vessel failure (18%) is attributed to the inability of the Pixhawk (and the vessels operating code) to handle

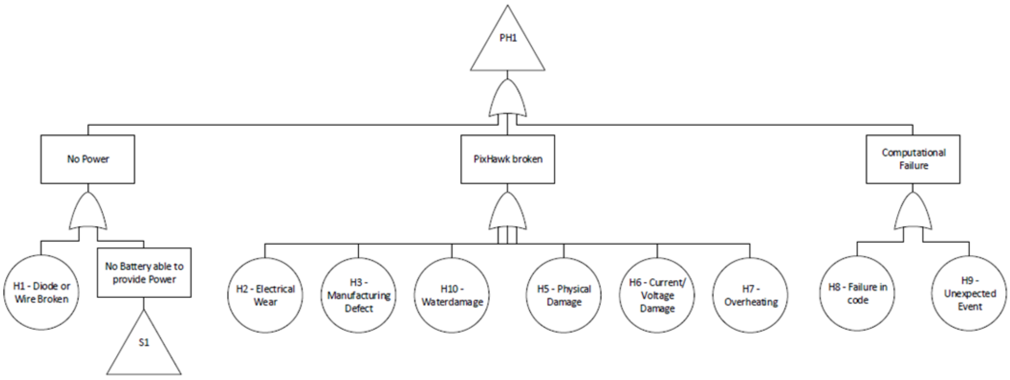

Figure 12: Example branch of the fault tree analysis

an event not part of the vessels normal operation and the lack of code specifically designed to handle the event. Since the probability of such an event is unknown, this is a subjective estimate by the team. Although subjective, this approach does provide a means to quantify the probability of success and, more usefully, to enable designs to be compared and developed with a quantifiable metric to maximize the probability of success.

5 Conclusion

This paper presented the design of the Peruagus, the University of Southampton 2018 Microtransat transatlantic autonomous surface vessel entry. The final vessel design is presented, including the system architecture, hull design, propulsion, steering, power and control systems. Experimental results are presented demonstrating that the vessel is able to self right, propel itself with low power and operate autonomously over a range of conditions. Furthermore, performance predictions are presented and based on a fault tree analysis the vessel is currently predicted to have a 60% chance of success. The vessel, a mono-hull, self righting, solar powered vessel is planned to be launched in 2018, in the Mircotransat non-sailing class, autonomous division, following an east-west route.

Acknowledgements

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