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Towards a hybrid powered passenger boat utilizing fuzzy controllers

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Abstract

This paper proposes fuzzy control strategies for a hybrid powered passenger boat. The proposed design incorporates a propulsion controller that aims to reduce fuel consumption by switching between electric motors and diesel engines depending on the boat's real-time situation. A hybrid on-board auxiliary power controller is also proposed that employs a combination of solar, wind, marine deep cycle batteries and diesel. MATLAB software is used to simulate and evaluate the proposed controllers. A prototype field-programmable gate array implementation is also constructed for validation purposes.

Keywords: Hybrid power, Solar energy, Wind energy, Fuzzy logic, Field-programmable gate array

1. Introduction

Research and development of cleaner and more efficient ship technologies has been ongoing for the past few decades. Much of this research started in response to concerns about rising fuel costs and reducing greenhouse gas emissions, such as carbon dioxide and nitrous oxides.

Currently, industry is moving towards adopting hybrid propulsion technologies in numerous transportation areas (land, sea, and air) to adapt to the modern energy paradigm. This is mainly due to environmental and climate changes, limited resources, and economic constraints.

Silvas et al. [1] discussed multiple hybrid electric architectures. Developing and finding the best solution for such an architecture is a complex problem that is addressed through various methods and algorithms. The size of on-board energy sources and storage systems for hybrid technologies deployed on a typical passenger vessel has been discussed [2]. A procedure for an optimal design is proposed. It consists of two criteria aiming to either run the engine at fixed or variable speed and power.

An electrical boat propulsion system is presented in [3]. The system is designed and analysed using various types of batteries and direct-current (DC) power converters to control its speed. A hybrid electric boat prototype is developed in [4]. The proposed hybrid energy storage and conversion system is modelled in software and experimental results confirm its validity.

Reduction of fuel consumption in marine hybrid powertrain vessels is realized by improving component operation [5]. The method optimizes propulsion component sizes to reduce fuel consumption by matching correctly sized components to their expected use.

A design and characterization tool, called an EMTool, (Electric Machine Tool) to reduce greenhouse gas emission in the transport sector has been presented [6]. The tool is integrated into a complete simulation workflow and offers the possibility to analyse, evaluate, and validate the performance of several topologies of electric machines.

A hybrid propulsion system for a fishing boat has been presented [7]. A combination of diesel engines and battery power is used for propulsion. The design battery capacity for the hybrid system depends on estimated power consumption and ship operation conditions. Two small solar/electric boats for race competitions, called the Nusrat and Muavenet, are presented [8]. The paper discusses their design, construction, and performance. These boats can be used to transport one or two people quickly over small distances.

A decision support system for a boat propulsion system selection is presented in [9]. The proposed model is designed using fuzzy logic based control algorithms. However, the fuzzy system is not used to select the energy sources for propulsion and on-board power. Instead, it is used to vary propulsion drives (jet drive, surface drive, and stem drive) which utilize the same energy source.

Corredor et al. [10] presented a power and efficiency analysis for a Plug-in Hybrid Electric Ship. The ship uses a hybrid electrical propulsion system in a parallel configuration. Simulation results show an overall system efficiency improvement of 25 – 30%. The cost of water based transportation is discussed in [11]. It was found that transportation over water is roughly three times as fuel efficient as shipping by rail. Solar powered boats are discussed in [12]. Electric motors and storage batteries charged by solar panels provide energy to electrical boat propulsion systems to reduce the use of fossil fuels.

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Exploring the production of hydrogen from seawater for use as fuel is discussed in [13]. It has been found that hydrogen can be generated from sea water using bulk aluminium and a metal alloy. However, the research stated that the seawater hydrogen formula is not yet economically feasible. Therefore, hydrogen based propulsion for boats is currently not a viable solution.

Hocke [14] describes the Hornblower hybrid 149 passenger catamaran marine vessel. The vessel uses a combination of diesel-powered generators, electric motors, vertical-axis wind turbines, and photovoltaic solar panels for propulsion and on-board power. The vessel can reach a service speed of 10 knots with a single engine. The vessel has a DC propulsion battery bank, two 1.2 kW wind turbines, and a 1.2 kW solar panel array. Power generated by the wind turbines and solar panel is used to operate the navigation system, lighting, and other electronic equipment.

An on-going eco-friendly solar-electric marine vessel project is presented in [15]. The goal is to develop a green passenger ferry (eco-commuter ferry) using hybrid propulsion technologies to make the ship cost effective and reduce harmful emissions. The vessel can use multiple power sources such as LNG and biofuel. It also has a power management system capable of optimizing battery performance and on-board electrical energy.

More recently, a green ship that utilizes renewable energy in the form of solar energy for auxiliary power is presented in [16]. A model is proposed where diesel generation, solar energy, and battery storage support auxiliary power demand. Any surplus energy could be sold when the ship is connected to the grid using tariff-driven power management.

This paper focuses on the development of intelligent controllers to select appropriate energy sources for powering a hybrid passenger boat at sea. Fuzzy logic is proposed as a solution to deal with difficulty in modelling the plant. A fuzzy system would also allow rules and weights to be relatively easily specified and tuned. The main purpose of the controllers is to reduce the consumption of fuel under favourable weather conditions, where solar and wind energy can be utilised.

2. Materials and methods

2.1 Proposed approach and possible boats

Sea transport in Fiji provides a two-way connection from the two principal islands (Viti Levu and Vanua Levu) to other small islands for transporting passengers and shipping essential products. However, fossil fuel-based marine vessels release emissions that are dangerous to the environment and people.

It is envisioned that boat propulsion can be provided by a combination of diesel fuel and wind. One intelligent controller will be utilised to choose between these energy sources. On-board auxiliary power can be supplied by a hybrid system consisting of solar panels, wind turbines, and a diesel generator. A second intelligent controller will be used to switch between these energy sources. It is proposed to utilize fuzzy logic for the controllers since it mimics non-binary human logic via human language rules. This can potentially enable easier adjustment of the controllers for various environment conditions. Fuzzy logic can handle this problem since there is likely to be imprecise and incomplete data. Since it is difficult to determine a model boat at present, fuzzy logic has the potential to produce a better solution than conventional control techniques. Moreover, the fuzzy logic controller rules are relatively easily adjusted for different environment conditions and boats.

The controllers receive data from various kinds of sensors and alternate between energy technologies depending on the weather and sea conditions. Two types of catamaran passenger ferries that can be upgraded with hybrid propulsion marine technologies for deployment in Fiji are discussed below.

The first is a passenger ferry [17] called Ocean Quest. The vessel is 21.9 m long and 6.7 m wide. It can carry 149 passengers and run at an average speed of 18 knots. The vessel is equipped with two 6125A Lugger diesel engines [18]. Each engine is capable producing 500 hp with more than 1300 pounds of torque.

The second example is a newly build catamaran passenger ferry [19]. The vessel's length is 15.8 m, breadth is 5.3 m, and depth is 4.85 m. It can carry 70 passengers and run at a cruise speed of 20 knots. The vessel is equipped with two D12 550 hp Volvo Penta marine type inboard diesel engines [20]. It is also equipped with a 12V/24 V electrical system and 10 marine type batteries.

It is proposed to modify the catamaran ferry architecture based on [19] or an equivalent boat to incorporate various propulsion and energy source technologies (solar, wind, and diesel). In the following sections, the design and prototype implementation of the fuzzy controllers for on-board power and propulsion power selection are presented.

2.2 Fuzzy control system overview

The control system consists of two fuzzy controllers, one for propulsion and another for on-board electrical power. An overall system block diagram of the two fuzzy controllers and their interconnection with the rest of the boat is shown in Figure 1. A high-level overview of the propulsion and onboard electrical power controllers is provided below.

For propulsion, a combination of Flettner rotors [21-22] and diesel engines is proposed. The engines could be either diesel-mechanical propelled or diesel-electric propelled. The control system will determine the number of diesel engines (1 or 2) to use based on wind speed information. It is assumed that an appropriately sized Flettner rotor is used to convert a sufficient proportion of the wind into the required propulsion under varying load conditions [22]. Figure 2 illustrates an overview of the propulsion controller. Further details of the rules and weights of the controller are provided in Section 2.3.

Wind speed information in the Fiji region can be obtained from [23]. Wind speed in Laucala Bay, Suva has been measured by Prasad [24]. Typical wind speed at the seashore is expected to be between 3 m/s and 5 m/s.

For on-board electrical power, a combination of solar, wind, marine deep cycle batteries, and diesel is proposed. Figure 3 illustrates an overview of the on-board power controller. More details of the rules and weights of the controller are provided in Section 2.3. It is assumed that a diesel generator supplies power for air-conditioning. This diesel generator could be around 15 kW and also act as a backup for other on-board electrical power needs. The deep cycle battery bank is sized to provide backup power for an eight hour trip. The battery system could be re-sized if longer trips are required.

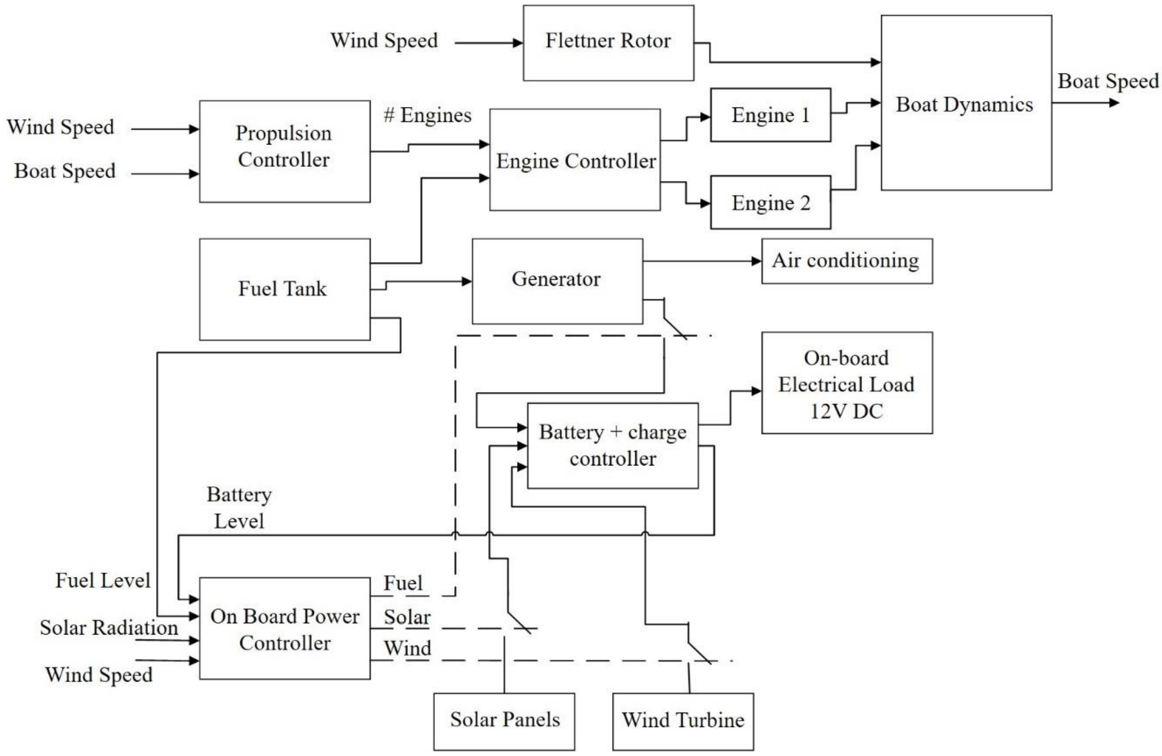


Figure 1 Overall system block diagram of the fuzzy controllers

Table 1 Estimated on-board electrical power

Item	Quantity	Load (kW)
6 W 12V DC LED light	20	0.12
50 W 12 DC outdoor waterproof floodlight	2	0.10
Navigation & Communication Equipment (estimate)	1	0.75
Entertainment (LED TV, DVD player, speakers) (estimate)	1	0.25
Total Load		1.22

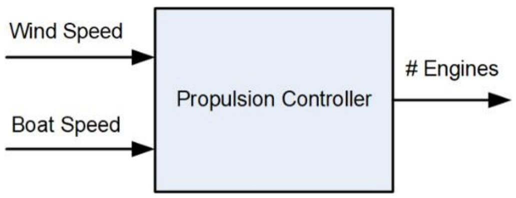


Figure 2 Overview of the propulsion controller

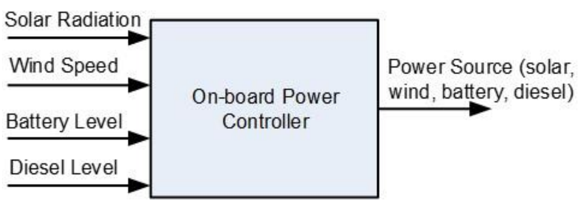


Figure 3 Overview of the on-board power controller

Typical solar radiation in the Suva area has been measured by [24]. Other sources for solar insolation information include the Energy Resources Inventory of the Fiji Islands [25] and Mario [26]. On a sunny day the solar insolation could vary from approximately 50 W/m^2 in the morning to approximately 1300 W/m^2 at around midday. When there is cloudy or overcast weather, solar insolation could vary from close to 0 to 800 W/m^2 depending on cloud cover. These radiation levels would be similar in the Fiji region and neighbouring Pacific Island countries such as Tonga and Samoa. As a rule of thumb, there is only slight variation in insolation for places within 25^0 latitude of the equator.

On-board electrical power use is estimated to be approximately 1.22 kW. This excludes power for air-conditioning, which is supplied by a diesel generator. Table 1 shows the estimated load based on typical on-board electrical equipment operating at 12 V DC.

Based on the roof and deck area of the ship (catamaran ferry [19]), approximately 28 Suntech 250 Watt monocrystalline solar modules [27] can be mounted. This has the potential to produce a maximum of 7 kW. However, based on the estimated on-board electrical power (Table 1) and accounting for variation in solar insolation and cable losses 4.5 kW should be sufficient. Hence, 18 solar panels should be able to supply sufficient power.

When there is insufficient solar radiation, energy from wind turbines could be utilized. It is proposed to use two small turbines based on the Whisper 100 wind turbine specifications [28]. The pair of wind turbines will have the potential to provide a maximum of 1.8 kW. On average the speed of the ship is expected to be between 15 and 20 knots. This would produce at least 0.6 kW to 1.4 kW of power. A drawback of using wind turbines is that they can create additional drag. Hence, it is preferred to use them only when solar radiation is insufficient.

For the battery bank sizing a duty cycle of eight hours using Trojan, SCS225, marine deep cycle batteries (12 V, 225Ah) [29] is assumed. This requires six batteries for the battery bank, assuming 10% losses and 70% discharge. It is assumed that a separate (additional) battery backup is available on the boat for the navigation and communication equipment.

2.3 Fuzzy controller descriptions

The MATLAB 2010a Fuzzy Logic Toolbox is used to develop the fuzzy controllers. All the controllers are Mamdani type (MATLAB's default type). The basic trapezoidal and triangular membership functions are used for simplicity. All membership function ranges, fuzzy rules and their corresponding weights have been empirically tuned to select "good" parameter values. The outputs of the various input combinations are viewed with MATLAB's surface viewer during empirical tuning.

The parameter settings for the fuzzy inference functions of the controllers are shown in Table 2. The MATLAB default settings are employed for the 'And', 'Or', 'Implication' and 'Defuzzification' functions. A gradual change in output is produced using the 'Sum' method for the 'Aggregation' function.

Table 2 Fuzzy inference function settings

Function	Method
And	Min
Or	Max
Implication	Min
Aggregation	Sum
Defuzzification	Centroid

Figure 4 illustrates the input and output membership functions for the propulsion controller. Wind propulsion speed is illustrated in Figure 4(a). Based on the wind speed information presented in Section 2.2, this input variable has a range of 0 to 18 knots. The range of the boat speed membership function (Figure 4(b)) is selected based on the typical and maximum boat speed. This is expressed in knots.

The output membership function (Figure 4(c)) selects the number of engines to be used for propulsion. This output is rounded to a whole number to determine whether one or two engines should be powered.

Table 3 shows the rule table for the propulsion controller. Preference to use one engine (engines = low) is given when the wind speed is high and a good (high) boat speed can be maintained.

Table 3 Propulsion controller rule table

Wind Prop. Speed	Boat Speed	Connection	Engines
Low	Low	and	High
Low	High	and	High
High	Low	and	High
High	High	and	Low

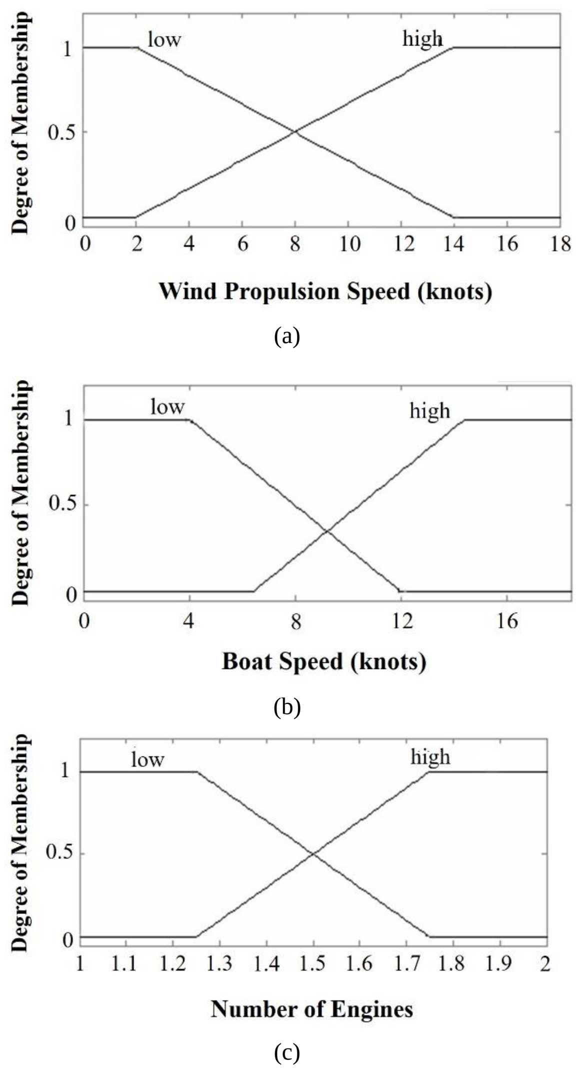


Figure 4 Propulsion controller input and output membership functions

Figure 5 illustrates the input and membership functions for the on-board power controller. The solar radiation (Figure 5(a)) and wind speed (Figure 5(b)) inputs have three membership functions to allow one, both, or neither of these sources to be utilized. For the solar radiation input, the range is selected based on the power curves of the Suntech solar modules [27] and typical solar radiation in Fiji. Power curves of the Whisper 100 wind turbines [28] and typical speed of the boat has been used to determine the range for the wind speed input.

Since a discharge of 70% is assumed for batteries, the low and not-low levels are based on 30% - 40% battery charge (Figure 5(c)). The low and not-low fuel levels are arbitrarily assumed (Figure 5(d)). The outputs of the controller indicate whether a power source is to be used or not. Figure 5(e) illustrates the 'use-solar' membership function. The other two outputs ('use-wind' and 'use-fuel') have similar membership functions. A 'use-battery' output is not required since it is assumed that the battery charge/ discharge is monitored by a charge controller/regulator.

Table 4 shows the rule table for the on-board power controller. The first three rules (1-3) determine if fuel needs to be used when solar and wind energy are both low. In rules 4-8, there would be sufficient power from solar radiation for

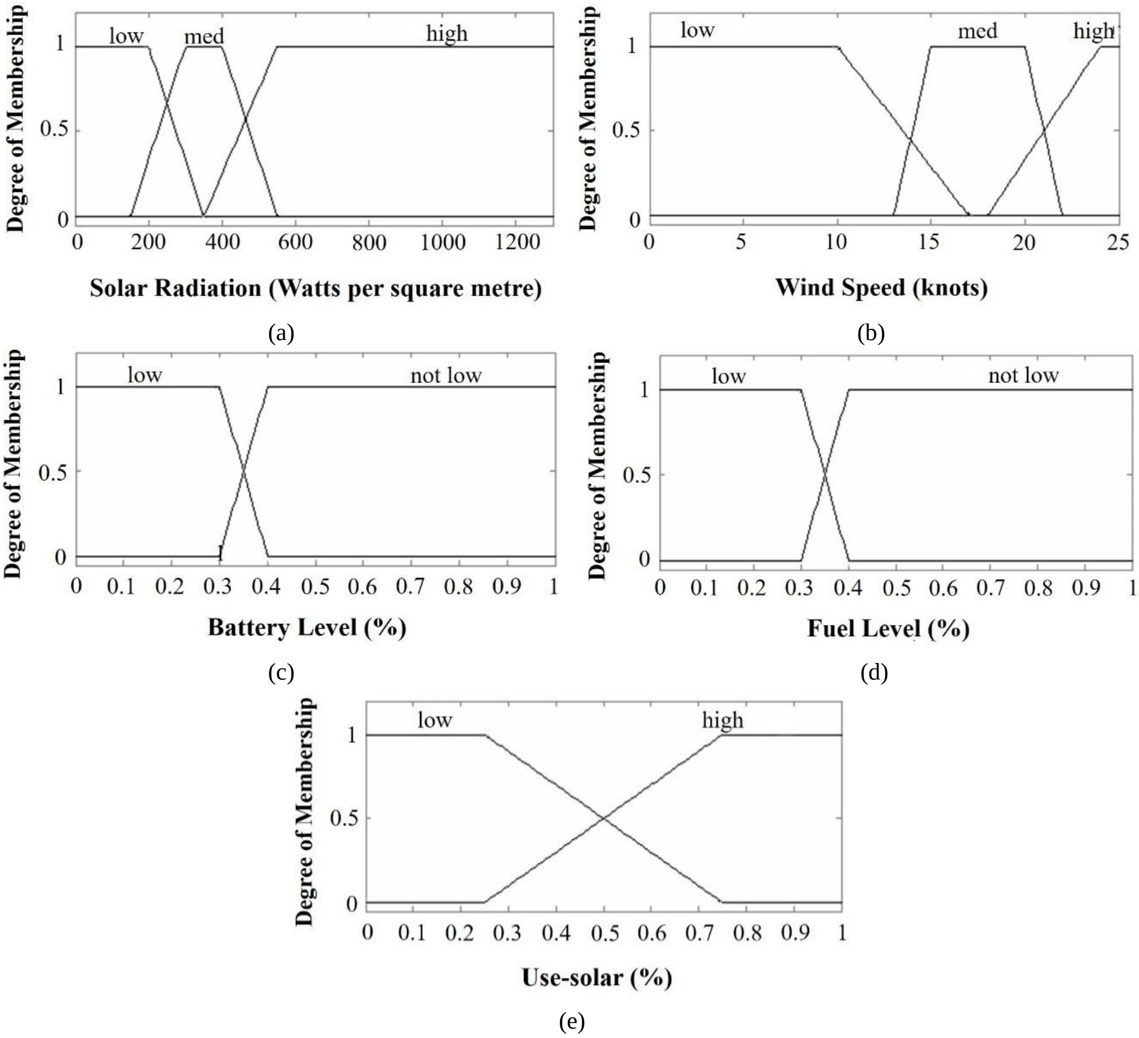


Figure 5 On-board controller input and output membership functions

Table 4 On-board power controller rule table

Rule no.	Inputs				Input Connections	Outputs		
	Solar radiation	**Wind speed**	**Battery level**	**Fuel level**		**Use-solar**	**Use-wind**	**Use-fuel**
1	low	Low	low	Not-low	And	Low	low	high
2	low	Low	low	Low	And	Low	low	-
3	low	Low	not-low	-	And	Low	low	low
4	high	high	low	-	And	High	high	low
5	high	high	not-low	-	And	High	low	low
6	high	medium	low	-	And	High	high	low
7	high	medium	not-low	-	And	High	low	low
8	high	low	-	-	And	High	low	low
9	medium	medium	-	-	And	High	high	low
10	medium	high	-	-	And	High	high	low
11	low	high	-	-	And	Low	high	low
12	low	medium	-	-	And	Low	high	low

the on-board load and to charge the battery bank if discharged. Hence, wind power is only utilized when the battery level is low (rule 4 and rule 6). When there is moderate power from both solar and wind, then it is preferred to use both sources (rule 9). In rules 10-11 there would be sufficient power from wind for the on-board load and to charge the battery bank if discharged. However, the two wind turbines produce less maximum power than the solar panel array, so it is preferred to use solar energy as well in rule 10. Rule 12 requires the use of wind energy when there is a moderate wind speed.

2.4 Hardware implementation

A prototype hardware implementation is made for validation purposes. It consists of mixed-signal circuitry

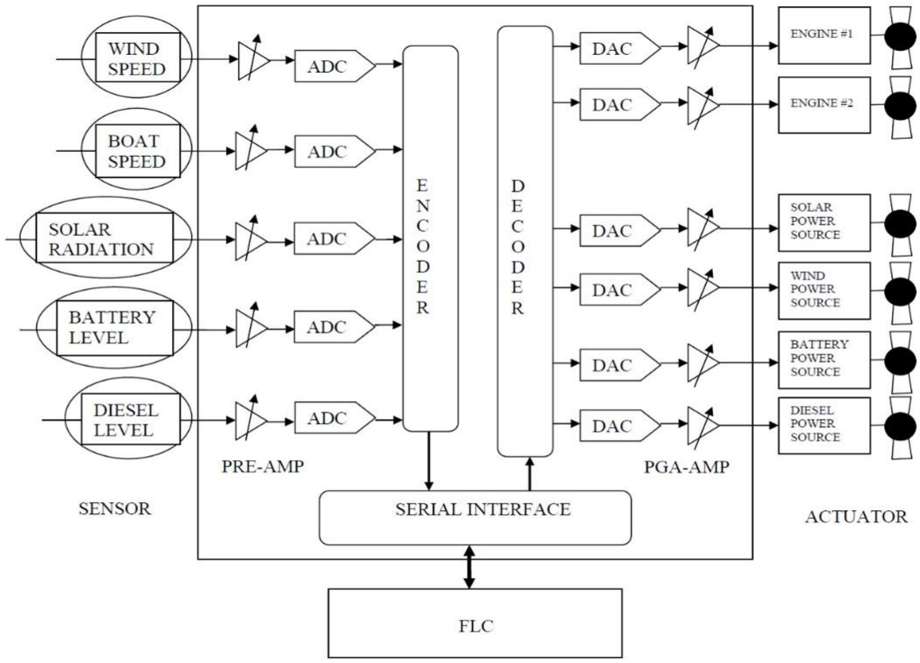
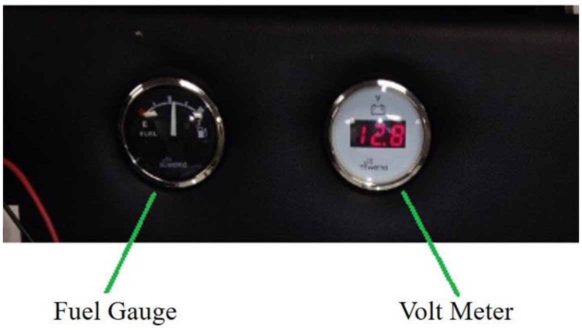
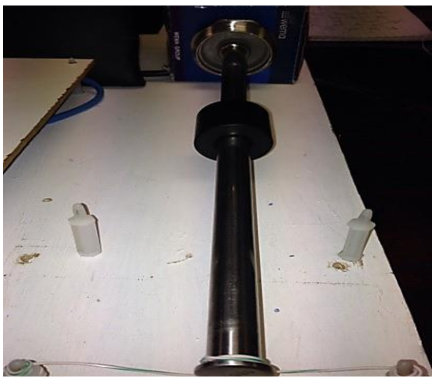


Figure 6 Proposed hardware system architecture



(a)



(b)

(c)

Figure 7 Sensors and signal generation equipment

(analogue and digital) as shown in Figure 6. Analog modules are implemented as discrete components. Digital modules are implemented in Very High-Speed Integrated Circuit (VHSIC) Hardware Design Language (VHDL) [30], on a Spartan-6 Field-Programmable Gate Array (FPGA) Development Board [31], using the Xilinx Platform Studio and Embedded Development Kit [32].

The overall system (Figure 6) has five analogue sensors at one end capable of capturing the wind speed, boat speed, solar radiation, battery level, and diesel level in real-time. The other end the system consists of relays and actuators to drive the two coupled propulsion engines and to select sources of energy. Pre-amplifiers and programmable gain amplifiers are used as input and output signals, respectively. Eight bit analogue-to-digital and digital-to-analogue converters are utilized for signal conversion. An encoder is used to select incoming digital signals, while a decoder is employed to decode outgoing digital signals. A serial interface transmits data between the encoding/decoding units and the fuzzy logic controller (FLC).

Figure 7 shows the main equipment used for sensors and signal generation. The fuel gauge display and volt meter sensor for diesel fuel and battery levels are shown in Figure 7(a). Figure 7(b) shows the fuel level sensor. Figure 7(c) shows the DC power supply used to emulate DC signals representing the solar and wind energy sources and boat speed information.

3. Results

3.1 Simulation results

The number of engines needed is based on the wind and boat speeds as illustrated in Figure 8. A smooth transition from one engine (Engines < 1.5) to two engines (Engines > 1.5) is seen.

Table 5 shows the simulation results for the on-board power controller using representative inputs to test the rules presented in Table 4 (Section 2.3). Each output (use-solar,

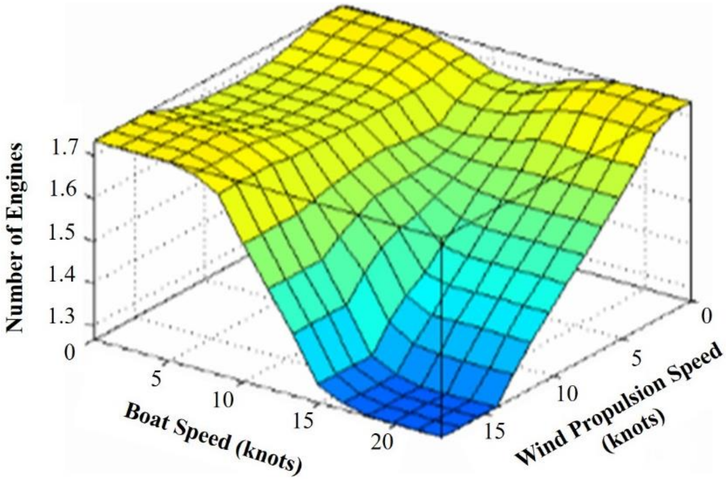


Figure 8 Engines output based on wind propulsion speed and boat speed

Table 5 Simulation results of on-board power controller

Rule no.	Inputs				Outputs		
	Solar radiation (W/m^2)	Wind speed (Knots)	Battery level	Fuel level	Use-solar	Use-wind	Use-fuel
1	100(low)	10(low)	0.3(low)	0.5(not-low)	0.27	0.27	0.73
2	100(low)	10(low)	0.2(low)	0.2(low)	0.27	0.27	0.5
3	100(low)	10(low)	0.4(not-low)	0.5(not-low)	0.27	0.27	0.27
4	800(high)	22(high)	0.3(low)	0.5(not-low)	0.70	0.70	0.30
5	800(high)	22(high)	0.4(not-low)	0.5(not-low)	0.71	0.30	0.30
6	850(high)	15(med)	0.3(low)	0.5(not-low)	0.71	0.62	0.29
7	850(high)	15(med)	0.4(not-low)	0.5(not-low)	0.71	0.29	0.29
8	800(high)	10(low)	0.4(not-low)	0.5(not-low)	0.73	0.27	0.27
9	400(med)	15(med)	0.4(not-low)	0.5(not-low)	0.70	0.57	0.30
10	400(med)	22(high)	0.4(not-low)	0.5(not-low)	0.69	0.59	0.30
11	100(low)	22(high)	0.4(not-low)	0.5(not-low)	0.30	0.70	0.30
12	100(low)	15(med)	0.4(not-low)	0.5(not-low)	0.29	0.62	0.29

use-wind and use-fuel) is switched ‘on’ if its output value is at least 0.5. The desired energy source is selected based on the sensor inputs.

3.2 Prototype hardware results

The prototype hardware implementation setup of the fuzzy controllers is shown in Figure 9. Figures 10 and 11 are screen-shots of the VHDL programming and input/output pin assignments for implementing the controller membership functions and fuzzy rules on an FPGA chip.

After compiling the propulsion controller software and interfacing the hardware with the software, ON/OFF LEDs representing output signals sent to the engines were observed based on the fuzzy rule implemented on the XILINX board and the wind speed and boat speed emulated signals generated by a DC power supply. Given scenarios of various weather conditions and the boat speeds, a decision is made on how many engines are to power the boat.

In a similar manner, the on-board power controller fuzzy rules were implemented and tested on an XILINX board. Signals representing solar radiation, wind speed, and battery charge were emulated using a DC power supply. ON/OFF LEDs representations of output signals for power source selection were observed. The hardware implementation outputs match the simulated outputs (Section 3.1) for both controllers.

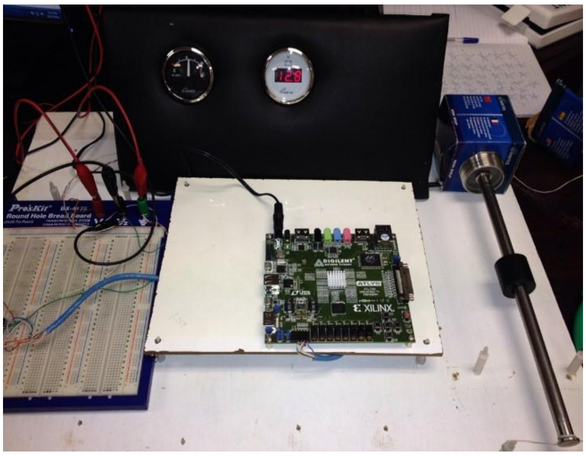


Figure 9 Prototype hardware implementation setup

4. Conclusions

The design and analysis of fuzzy controllers for hybrid propulsion and on-board power source selection for sea transportation is presented. Controllers were developed based on a catamaran ferry architecture for use in the South Pacific. A catamaran ferry can provide two-way connections from the main islands to smaller islands to provide passenger and freight transportation.

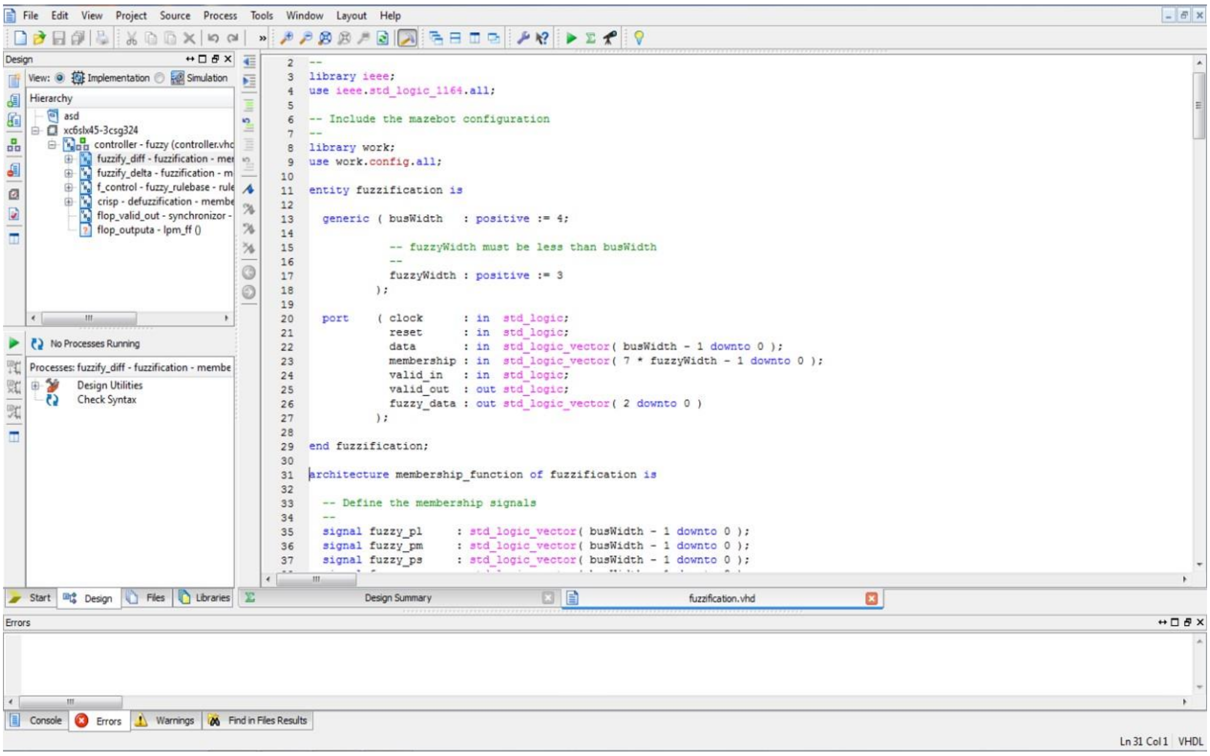
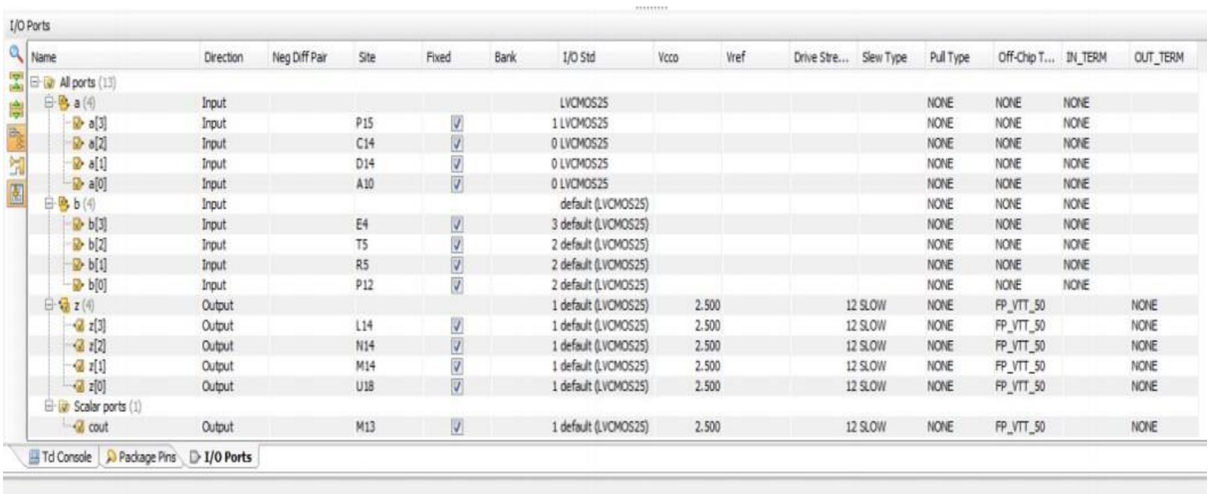


Figure 10 VHDL code



I/O Ports

Name	Direction	Neg Diff Pair	Site	Fixed	Bank	I/O Std	Vcco	Vref	Drive Stre...	Slew Type	Pull Type	Off-Chip T...	IN_TERM	OUT_TERM
All ports (13)														
a (4)	Input					LVCMOS25					NONE	NONE	NONE	
a[3]	Input		P15	✓	1	LVCMOS25					NONE	NONE	NONE	
a[2]	Input		C14	✓	0	LVCMOS25					NONE	NONE	NONE	
a[1]	Input		D14	✓	0	LVCMOS25					NONE	NONE	NONE	
a[0]	Input		A10	✓	0	LVCMOS25					NONE	NONE	NONE	
b (4)	Input					default (LVCMOS25)					NONE	NONE	NONE	
b[3]	Input		E4	✓	3	default (LVCMOS25)					NONE	NONE	NONE	
b[2]	Input		T5	✓	2	default (LVCMOS25)					NONE	NONE	NONE	
b[1]	Input		R5	✓	2	default (LVCMOS25)					NONE	NONE	NONE	
b[0]	Input		P12	✓	2	default (LVCMOS25)					NONE	NONE	NONE	
z (4)	Output				1	default (LVCMOS25)	2.500		12	SLOW	NONE	FP_VTT_50		NONE
z[3]	Output		L14	✓	1	default (LVCMOS25)	2.500		12	SLOW	NONE	FP_VTT_50		NONE
z[2]	Output		N14	✓	1	default (LVCMOS25)	2.500		12	SLOW	NONE	FP_VTT_50		NONE
z[1]	Output		M14	✓	1	default (LVCMOS25)	2.500		12	SLOW	NONE	FP_VTT_50		NONE
z[0]	Output		U18	✓	1	default (LVCMOS25)	2.500		12	SLOW	NONE	FP_VTT_50		NONE
Scalar ports (1)														
cout	Output		M13	✓	1	default (LVCMOS25)	2.500		12	SLOW	NONE	FP_VTT_50		NONE

Figure 11 Assigned input/output pins

Based on real input data for wind speed, solar radiation, battery capacity, and fuel consumption sensors, a simulation and prototype hardware results indicate that it is possible to reduce fuel consumption and greenhouse gas emissions through the use of this system. The usability of solar and wind energy is dependent upon favourable weather conditions. The fuzzy controllers may need to be tuned for use under various environmental and load conditions. This can be achieved via adjustment of the rules and weights.

Future work will include implementing and testing the proposed the system on an actual ferry travelling between the main islands of Viti Levu and Vanua Levu. Performance of the hybrid boat can then be compared with fuel only boats and other hybrid systems.

5. Acknowledgements

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