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Autonomous sailboat design: A review from the performance perspective

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ABSTRACT

Autonomous sailboats are promising platforms for long-term marine science missions and have become a research area of increased interest over the last two decades. To date, dozens of distinctive autonomous sailboats have been designed and notably employed in numerous tasks. Some literature lists and reviews the various designs of the existing autonomous sailboats; however, no comprehensive work connects the design to the performance requirements of various application scenarios. This paper first reviews and summarizes the existing designs from the perspective of critical performance in marine science missions, further pointing out the present state and the logic behind the designs. We then identify factors that hinder further performance improvement of autonomous sailboats through statistics and analysis of existing designs. We finally describe how the autonomous sailboat community should best address these challenges with technology from other disciplines. This article can provide references for designers of autonomous sailboats and inspire the community to eliminate the limitations they are facing. Additionally, making autonomous sailboats more powerful platforms can facilitate marine science research, such as research on ecosystems, biogeochemistry, and meteorology.

1. Introduction

In recent years, the related research on marine ecosystems, biogeochemistry, and meteorology has been extended to the open sea, which has increased the urgent demand of the scientific community for long-term surface data acquisition platforms (Hotaling and Kocak, 2014; Stammer et al., 2016; Visbeck, 2018). Directly driven by abundant wind energy, autonomous sailboats are endowed with good endurance (Cokelet et al., 2015; De Robertis et al., 2019; Stelzer and Jafarmadar, 2011). In addition to their low cost (Miller et al, 2015a, 2015b), low noise (Silva et al., 2013), and moderate transition capacity (Cruz and Alves, 2008a,b), autonomous sailboats are promising platforms (Chai et al., 2020; Cruz and Alves, 2008a,b; Rynne and von Ellenrieder, 2009), and significant relevant progress has been attained over the past 20 years (Abril et al., 1997; Elkaim, 2001).

Designing an autonomous sailboat with good performance requires sufficient insights. First, different tasks have different performance requirement weights. Long-distance transfer tasks require better endurance, while tracking tasks may pay more attention to sailing speed. For platforms that work in harsh seas, survivability is the primary performance. Second, the sea is harsh and changeable. Operation platforms must withstand most environmental conditions; therefore, performance conflicts arise. The choice of trade-off requires sufficient experience and wisdom. Moreover, as autonomous sailboats are strongly affected by the environment, the process of comparing and evaluating different designs is complicated.

At present, designers, from academic organizations to commercial companies, have developed dozens of distinctive autonomous sailboats, which play essential roles in multitudinous tasks, such as ocean floor mapping (Saildrone Surveyor), marine biological surveys (Klinck et al., 2009; Mordy et al., 2017), long-term ocean observations (Cokelet et al., 2015; Cross et al., 2015; Ghani et al., 2014; Meinig et al., 2015; SailBuoy - Unmanned Surface Vessel, 2020), and water mass tracking (Kilpin, 2014; Rathour, 2016). The literature describes works on performance improvement of autonomous sailboats, including structural durability (Domínguez-Brito et al., 2016; Sauze et al., 2006; Sauzé and Neal, 2011a), energy self-sufficiency (Alvira and Barton, 2013; Baker et al., 2016; Bruget et al., 2014; Dahl et al., 2015; Lavigne et al., 2016), overturning resistance (Alves and Cruz, 2008; Giger et al., 2009; Neal, 2006), sailing speed (Dhomé, 2018; Tretow, 2017), etc. Currently, autonomous sailboats can sail for dozens or even hundreds of days (Cokelet et al., 2015; Cross et al., 2015; De Robertis et al., 2019; Meinig

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et al., 2015; Vazquez-Cuervo et al., 2019) or complete feats such as crossing the Atlantic (SailBuoy - Unmanned Surface Vessel, 2020) and circumnavigating Antarctica (Stein, 2019).

Although some of the literature (Silva et al., 2019; Stelzer and Jafarmadar, 2011) listed and reviewed existing autonomous sailboat designs, no related work has been performed from the perspective of performance. Therefore, this paper first reviews and summarizes the existing designs from the perspective of critical performance in marine science missions, aiming to connect the design to performance requirements and clarify the logic behind these designs. Then, through the analysis of the methods adopted by the designer to meet performance requirements design and statistical analysis, we reveal the cause of the bottleneck in the performance improvement of the current autonomous sailboat designs. In response to these factors, we finally introduce technologies in related fields that can be used as potential solutions.

This paper provides comprehensive references in terms of design considerations and parameters. It is important to note that the field of autonomous sailboat design is still far from mature and potential technologies are introduced in this paper. Thus, we aim to inspire designers and thus enable autonomous sailboats to become more powerful tools for marine science research. In this paper, existing designs are reviewed in Section 2, considering the following four essential characteristics: structural durability, energy self-sufficiency, overturning resistance, and sailing speed. The factors limiting further performance improvements of autonomous sailboats are summarized in Section 3. Section 4 describes the future development direction prospects of autonomous sailboat design. In Section 5, conclusions are presented.

2. Present state: review of the designs from the perspective of performance

Performance is usually both the starting point and goal of design. Reviewing existing designs from the perspective of performance can be helpful when comparing different designs, analysing the design ideas behind them, and revealing core design issues. The unique feature of autonomous sailboats compared with other platforms is that they are driven by sails. Therefore, autonomous sailboats are structural fragile, energy-saving, easy to capsize, and their speed is easily affected. Therefore, we review and analyse existing designs from four performance aspects: structural durability, energy self-sufficiency, overturning resistance, and sailing speed.

2.1. Structural durability

Structural durability is the capability of a component to withstand the loads encountered in service over a specified period of use without failure or unacceptable degradation. Considering that autonomous sailboats often work in extremely harsh environments (for example, wind speeds of 46 knots (Cokelet et al., 2015) and wave heights of 14.3 m (SailBuoy - Unmanned Surface Vessel, 2020)), structural durability is assigned the highest design priority (Alves and Cruz, 2014; Cruz and Alves, 2008a,b; M\aasala and others, 2018; Naveau et al., 2013; Sauze et al., 2006). Table 1 presents the failure cases attributed to insufficient structural durability reported in the application-related literature (Klinck et al., 2016; Meinig et al., 2015) and on the Microtransat Challenge website (Microtransat-History, 2020), a transatlantic race for autonomous boats.

The most vulnerable component of an autonomous sailboat is its sail; the hull, keel, and rudder are also at risk of failure. The cause of damage to the sail and its actuator is usually impact caused by high-energy wind and waves, fatigue, and artificial damage caused by passing ships. The following two scenarios are very threatening for the hull, keel, and rudder: driven into nearshore areas by superimposed winds and currents and encountering passing ships or fishing operations. Both may cause severe entanglement and collision.

To enhance the structural durability of the vessels, traditional soft

Table 1
Reported failure cases attributed to insufficient structural durability.

Platform	Year	Failed component	Failure time after departure[a]	Cause of failure
Breizh Spirit	2011	Sail	2–8 days	Unknown
Breizh Spirit DCNS	2012	Sail	5 days-2 months	Washed ashore
Roboat	2012	Sail actuator	1 day	Strong winds
Erwan 1	2013	Hull	4–48 days	Unknown
Snoopy Sloop 9 (1)	2014	Keel and rudder	1 day	Washed ashore
Snoopy Sloop 9 (2)	2014	Rudder	2 days	Washed ashore
Saildrone	2014	Sail actuator	NA	Strong winds
ABoat Time	2015	Hull and rudder	9 days	Intercepted by a fishing boat
That'll Do	2016	Hull, mast, keel, and rudder	5–12 days	Collision with passing ship
Trawler Bait	2016	Sail	16 days	Intercepted by a fishing boat
Gortobot v4	2019	Sail	2 days	Unknown

[a] Since the platforms are recovered after a certain period, the time of failure is expressed as the effective working time to the time of recovery.

sails (SailBuoy - Unmanned Surface Vessel, 2020; Voosen, 2018) have increasingly been replaced with vertical airfoils, i.e., wing sails. The traditional soft sail with thousands of years of history is suitable for long-distance sailing with crews (Neal et al., 2009; Stelzer and Jafarmadar, 2011). However, prone-to-wear soft sails (Miller et al., 2015b; Neal et al., 2009; Rynne, 2008) and prone-to-entanglement riggings (Sauze et al., 2006) are not suitable for automatic systems without maintenance. In contrast, wing sails are more reliable due to their solid profiles (Elkaim, 2001) and embedded actuators (Enqvist et al., 2016; Hansen, 1996, p. 1; Neal et al., 2009). Moreover, in contrast to soft sails, which have an air performance that severely degenerates after damage, wing sails usually do not fail (Tretow, 2017), as depicted in Fig. 1(a). Detailed information on platforms equipped with wing sails has been provided by Silva et al. (2019). Another way to improve sail durability is to increase redundancy via the adoption of dual (wing) sails, as depicted in Fig. 1(b). Platforms equipped with dual sails include the ARC (Sauze et al., 2006), MOOP3 (Sauzé and Neal, 2011a), A-Tirma G2 (Domínguez-Brito et al., 2016), and the Shanghai Jiao Tong University (SJTU) prototypes (Du et al., 2018). In addition to the realization of durability redundancy, dual sails can greatly reduce the overturning moment and act as air rudders (Domínguez-Brito et al., 2016; Neal et al., 2009) to enhance the manoeuvrability of autonomous sailboats.

Sail actuators have been designed so that the actuator can be locked without the need to continuously maintain the position (Miller et al., 2013). As another technical route, the SailBuoy adopts a free-rotating wing sail with a caging device (SailBuoy - Unmanned Surface Vessel, 2020), as shown in Fig. 1(c). Although the sail cannot be precisely controlled, it provides sufficient durability. With this configuration, SailBuoy became the first autonomous sailboat ever to complete a transatlantic voyage. Similarly, autonomous sailboats such as Atlantis (Elkaim, 2001, 2006), Saildrone (Cokelet et al., 2015; Meinig et al., 2015), ASPire (Friebe, 2019; Friebe et al., 2017; M\aasala and others, 2018), and Maribot Vane (Tretow, 2017) adopt free-rotating self-trimming wings to effectively reduce the load acting on the actuators. However, the reduction in energy consumption is more pronounced, and therefore, self-trimming wings are described in Section 2.2.

Regarding hull manufacture, glass fibre and carbon fibre materials, which exhibit good resistance to corrosion and collisions, are commonly applied. Certain designs incorporate additional hull reinforcement and protection measures to minimize the damage caused by collisions and scratching. The bow and stern, which are prone to collision, can be wrapped in polyurethane foam (Neal, 2006). Watertight bulkheads

Table 2
Review of existing designs based on dimensionless numbers. Each dimensionless number reflects a specific performance aspect of the sailing speed.

Reference	Platform name	Length (m)	Disp (kg)	LDR	L/B	SA/D	B/D	Reference	Platform name	Length (m)	Disp (kg)	LDR	L/B	SA/D	B/D
Abril et al. (1997)		1.0	4.5	6.2	4.2	13.4		Fernandes et al. (2016)		1.9	20	7.0	9.5		15%
(Elkaim, 2001, 2006)	Atlantis[b]	7.2	150	13.6	2.4	27.5	50%	Kang et al. (2016)		1.5	15	6.1	3.2	18.9	
(Neal, 2006; Sauze et al., 2006)	AROO	1.5	12	6.6		4.5	29%	Rathour (2016)	SOTAB-II	2.6	150	5.0	3.5	2.0	20%
Stelzer et al. (2007)	Robbe Atlantis	1.4	17.5	5.3	4.1	12.7	63%	Augenstein et al. (2017)		1	6	5.5		7.3	5%
(Alves et al., 2008; Alves and Cruz, 2008)	FASt	2.5	50	6.8	3.7	27.3	40%	(Friebe, 2019; Friebe et al., 2017; M\aasala and others, 2018)	ASPire	4.2	370	5.8		4.0	47%
Briere (2008a)	IBOAT	2.4	35	7.3	6.0	14.0	40%	Tretow (2017)	Maribot Vane	4.2	280	6.4	5.3	7.0	
(Rynne and Ellenrieder, 2010; Rynne and Von Ellenrieder, 2008; Rynne, 2008)	WASP	4.2	275	6.5	5.3	10.6	82%	Submaran (2017)	Submaran S10[a]	4.14	127	8.2			
Giger et al. (2009)	Avalon[b]	4.0	440	5.2	2.8	6.9	36%		Datamaran[a,b]	2.5	85	5.7	1.5		
Domínguez-Brito et al. (2016)	A-Tirma G2	2.0	43	5.7	4.1	1.9		Microtransat-History (2020)	Breizh Spirit DCNS	1.40	13	6.0	2.5		
Klinck et al. (2009)	AAS Endurance	3.8	300	5.6		10.0	20%		Snoopy Sloop 8	1.20	14	5.0	4.3		
Neal et al. (2009)	MOOP	0.7	4	4.5		0.3			Snoopy Sloop 11	1.33	14.6	5.4	4.6		
Koch and Petersen (2011)	FHsailbot	1.5	15	6.2	4.6	10.7			Erwan 1	3.65	300	5.5	4.2		
Koch and Petersen (2011)	Saudade	1.1	9	5.4	4.3	12.0			ABoat Time	1.20	18	4.6	3.4		
Leloup et al. (2011)	Breizh Spirit1	1.5	13	6.4	4.3	15.5			That'll do	1.40	10	6.5	3.0		
	Breizh Spirit2	2.3	55	6.0	2.9	13.8			Gortobot v3	1.81	8.1	9.0	3.5		
	Breizh Spirit3	1.7	13	7.2	3.8	13.6			Breizh Tigresse	1.44	28	4.7	2.4		
Stelzer and Jafarmadar (2012)	ASV Roboat	3.7	300	5.6		12.0	20%		OpenTransat (2016)	2.36	45	6.6	3.3		
Miller et al. (2013)	SOA	1.9	52.2	5.0	5.6	13.6			OpenTransat (2019)	2.00	47	5.5	6.3		
Miller et al. (2013)	W2H	1.9	44	5.2	3.9	14.4			Gortobot V2	0.79	5.4	4.5	2.5		
(Anthierens et al., 2014; Naveau et al., 2013)	Marius	2	70	4.9	2.5	17.1	50%		Phil's Boat	0.85	7	4.4	3.3		
Cabrera-Gámez et al. (2014)	A-Tirma	1	4.3	6.1	4.1	23.1			That'll Do Two	1.40	10	6.5	1.8		
Ghani et al. (2014)	SailBuoy	2	60	5.1	4.0	6.5			SeaLeon	1.80	50	4.9	3.6		
Miller et al. (2014)	ARRTOO Prototype[a]	1.95	29.5	6.3	4.1				EC-Crossing	1.05	10	4.9	4.8		
(Cokelet et al., 2015; Meinig et al., 2015)	Saildrone[c]	7	750	7.7	2.7	6.1			Brave Puffin	1.80	22	6.4	9.0		
Cruz et al. (2015)	Zarco ASV[a,b]	2.5	50	6.8					Bearly Assailable	1.20	26	4.1	3.3		
Miller et al. (2015a)	Sea Quester	1.9	25.5	6.6	6.5	30.8	43%		Endeavour	1.05	10	4.9	4.8		
Miller et al. (2015b)	MaxiMOOP	1.2	23	4.2	3.4	12.4			Pinta	2.95	450	5.6	2.5		
(An et al., Unpublished results.)	Seagull	3.45	155	6.4	2.9	4.1	20%	(Saildrone Surveyor)	Saildrone Surveyor[c]	22	12700	9.4		7.5	

$$SA/D = \left(\frac{Sail\ \ area}{Volume\ \ of\ \ displacement}\right)^{\frac{2}{3}} \quad LDR = \left(\frac{Waterline\ \ length}{Volume\ \ of\ \ displacement}\right)^{\frac{1}{3}}$$

Notes:
[a] Sail-propeller hybrid propulsion platforms.
[b] Catamarans.
[c] Monohull mode.

(a) (b) (c)

Fig. 1. Wing sails. (a) The partly smashed wing sail still enables Saildrone to be retrieved remotely during a mission (Gibb, 2019). (b) Dual sails improve the durability by increasing the redundancy (Domínguez-Brito et al., 2016). (c) The free-rotated sail provides sufficient structural durability, making SailBuoy the first autonomous sailboat in history to complete a transatlantic voyage (SailBuoy - Unmanned Surface Vessel, 2020).

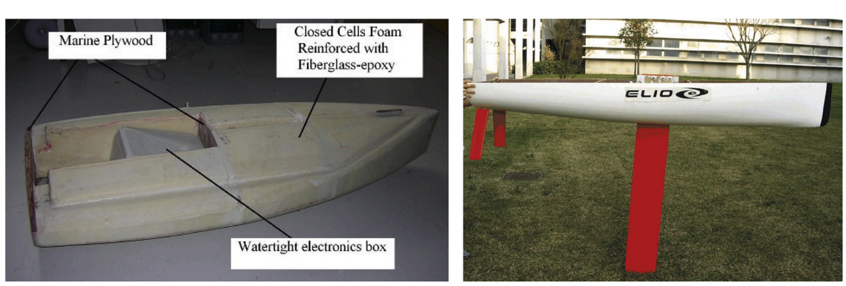
(Leloup et al., 2011), waterproof boxes (or tubes) (Elkaim, 2001; Leloup et al., 2011; Sliwka et al., 2009), and styrene foam plastic fillers are used in Snoopy and Breizh Tigresse, Endeavour, EC-Crossing, Brave Puffin, and OpenTransat to improve the sink resistance and provide electronic equipment protection (Boat Details-Team Joker, 2014; Stenersen, 2016). Fig. 2(a) shows the hull of Breizh Spirit 3 as a typical case of hull enhancement. Regarding the rudders, Atlantis (Elkaim, 2001), ARC (Sauze et al., 2006), FASt (Alves and Cruz, 2008), IBOAT (Briere, 2008a), Avalon (Giger et al., 2009), and A-Tirma G2 (Domínguez-Brito et al., 2016) include twin rudders, as depicted in Fig. 2(b), which can increase the durability redundancy and ensure manoeuvrability under severe heeling (Giger et al., 2009; Sauze et al., 2006; Sliwka et al., 2009).

2.2. *Energy self-sufficiency*

Almost all platforms are powered by electricity for convenience. Navigation via the assimilation of abundant wind by sails rather than the transformation of stored energy by the main engine makes autonomous sailboats advantageous in terms of endurance (Smith, 1989). However, power is required for frequent adjustments of the sails and rudders, sampling of scientific payloads (Adornato et al., 2009; Drifters, 2003), and transmission of data and commands (Hotaling and Kocak, 2014). Most platform acquisition energy supplements mainly rely on solar panels, which are vulnerable to cloudy weather conditions, high latitudes, and salt spray fouling (Augenstein et al., 2017; Briere, 2008a; Sauzé and Neal, 2011b). Although designers have adopted measures (Friebe et al., 2017; Guo et al., 2011; Jaulin and Le Bars, 2014; Miller et al., 2014; Naveau et al., 2013) to improve energy harvesting, ensuring energy self-sufficiency for continuous scientific work remains challenging. The gap between energy harvesting and energy consumption may require high-capacity batteries (Sauzé and Neal, 2008a, 2011b) and backup fuel cells (Giger et al., 2009; Klinck et al., 2009) and may lead to a decrease in task performance or endurance (Júnior et al., 2013; Ulysse et al., 2019).

According to statistics, 1 m^2 marine solar panels can produce approximately 10–35 W on average when considering the alternation of day and night and the probability of inadequate sun coverage (Rynne and von Ellenrieder, 2009), which is approximately 1/6–1/3 of the ideal state (Augenstein et al., 2017; Briere, 2008a; Sauzé and Neal, 2011b). To improve energy harvesting, the maximum number of solar panels is deployed on sails and decks (Fig. 3). Moreover, the ASPire (Friebe et al., 2017) adopted innovative solar panels to track the direction of the sun

Fig. 3. Solar panels on the Datamaran Mark8 (PLATFORM — Autonomous Marine Systems, 2019). To enhance energy harvesting, Datamaran Mark8 makes full use of its large deck area to arrange solar panels.



(a) (b)

Fig. 2. Structural durability enhancement of the hull and rudder. (a) Watertight bulkheads of the hull of Breizh Spirit 3 (Leloup et al., 2011). (b) FASt equipped with a twin rudder (Alves et al., 2008).

by adjusting the azimuth angle (Fig. 4). It has been reported that the annual energy output can be increased by 50% compared to horizontally installed panels. Specific platforms adopt vertical-axis wind turbines to obtain additional energy, especially at night (Guo et al., 2011; Miller et al., 2014; Naveau et al., 2013). Jaulin and Le Bars (2014) proposed a unique energy harvesting method. The main idea involved the application of a station-keeping-mode platform as a windmill—pulling with swinging sails. As reported, this approach generates 93 W of electrical energy on average at a wind speed of 4 m/s.

Excluding the scientific payloads, which are usually different, the energy consumption of autonomous sailboats mainly includes three parts. The functional module comprises the main computer, sensors, and communication system. The driving module is the sail actuator, and the steering module is the rudder actuator.

The energy consumption of the functional module is related to the hardware selection and the operational frequency instead of the general size of the platform. As shown in Fig. 5, functional modules account for 5%–86% of the total consumption of certain platforms. To reduce energy consumption, designers have adopted various management strategies linking operation decisions to the remaining power (Dahl et al., 2015; Sauzé and Neal, 2008b, 2011b) or frequency reduction (Alves et al., 2008; Baker et al., 2016; Eriksson and Friebe, 2015; Sauzé and Neal, 2011b) of the main computer in a low-battery or idle state.

The driving module accounts for 13%–86% of the total consumption. Certain autonomous sailboats use balanced rigs (as depicted in Fig. 6) to reduce the high energy consumption of traditional soft sails under high loads (Ménage et al., 2014). The headsail and mainsail of the balanced rig are positioned on the same beam instead of on separate beams. This configuration brings the centre of effect closer to the mast with a shorter arm, which produces a more balanced wind load distribution, effectively reducing the energy consumption of the sail actuator and improving the sail durability. It has been reported that the load on the sail actuator can be reduced by more than 50% (Giger et al., 2009), the energy consumption can be reduced by two-thirds (Stelzer and Dalmau, 2013), and the impact on aerodynamic performance can be ignored (Stelzer and Dalmau, 2013). Wing sails are generally heavy and sensitive to the attack angle (Enqvist et al, 2016, 2017; Kilpin, 2014). The frequent and precise control of wing sails is a highly energy-consuming task. As an improvement, self-trimming wings have been developed. The self-trimming wing was first proposed in 1983 (Newman and Fekete, 1983) and was first applied to the autonomous sailboat Atlantis in 2001 (Elkaim, 2001). Compared to a wing sail directly driven by the actuator, a self-trimming wing can rotate freely and is controlled by another smaller surface that is usually mounted behind it, namely, the tail

Fig. 4. Smart solar panels on the ASPire (Friebe, 2019). Smart solar panels can automatically track sunlight to improve energy harvesting.

(Fig. 7). Similar to a wind vane, the controlled tail applies the wind power to adjust the main wing to the desired angle (Elkaim, 2008; Elkaim and Boyce Jr, 2007). On the one hand, Elkaim (2008), Enqvist et al. (2016), and Tretow (2017) noted that the self-adjusting system simplifies the complexity of the control system and dramatically reduces the energy consumption associated with the adjustment and position keeping of the main wing. On the other hand, the tail provides passive stability – when the wind direction changes slightly, the self-trimming sail can absorb gusts and automatically maintain a fixed angle of attack (also a fixed lift coefficient). This feature decouples the propulsion system from the navigation control system to a certain extent, effectively downgrading the control frequency and further reducing energy consumption (Augenstein et al., 2017; Dhomé, 2018).

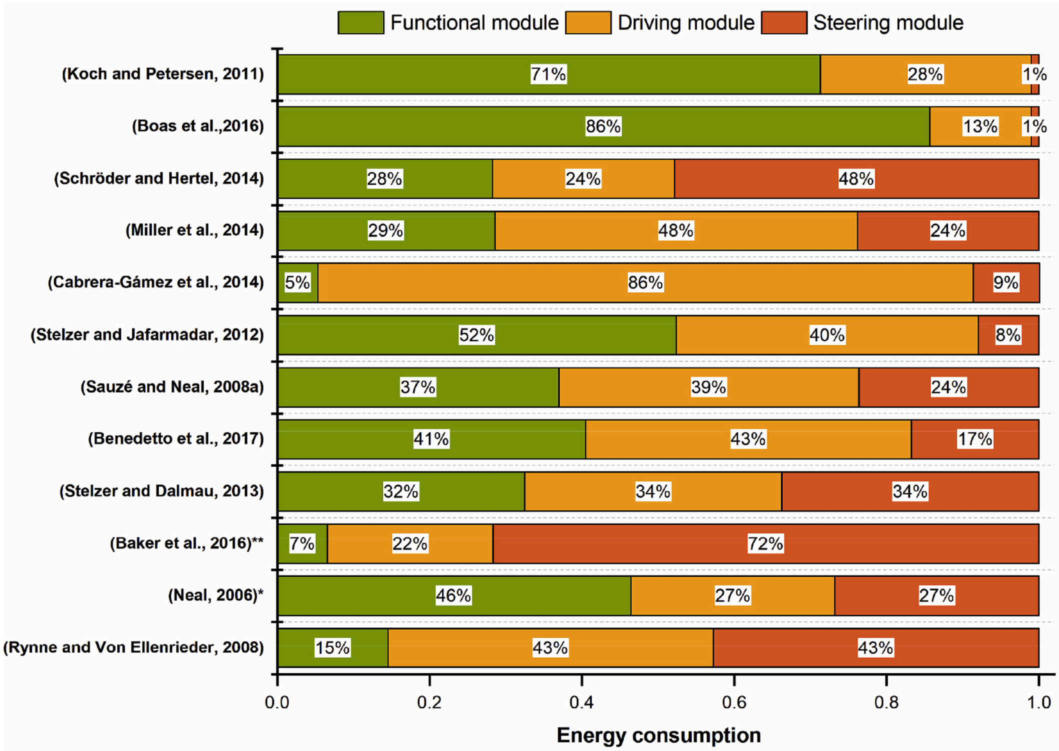
In regard to the steering module, self-steering systems, as depicted in Fig. 8 have been implemented to save energy. The history of the self-steering system is much longer than that of autonomous sailboats. Since at least the 1920s, crewed sailboats have adopted self-steering systems (Alves and Cruz, 2008; Letcher and others, 1976; Stelzer et al., 2007). Currently, it remains in use for long-distance sailing voyages to reduce the operational burden on sailors. Similar to the self-trimming sail, the main concept of the self-steering system is to link the rudder to the wind vane mechanically. When the wind direction changes slightly, the rudder is automatically adjusted without energy consumption. Application to autonomous sailboats was first reported in 2011 on the L'improbable of the ENSTA-Bretagne robot team (Sliwka et al., 2011). The system was mounted on the bow to avoid any gears between the rudder and vane. In another case, the Maribot Vane (Tretow, 2017) adopted both a self-steering system and a self-trimming wing. Since the main wing turns with the wind, an additional wind vane was not included, and the main wing was directly connected to the rudder through a clutch. Tests revealed that this configuration can automatically maintain the heading (Dhomé, 2018; Ulysse et al., 2019) in the automatic mode while switching to the active servo-controlled mode when needed.

2.3. Overturning resistance

In the naval architecture field, the term stability usually describes the ability of a ship (the hull itself) to float in the upright position and, if inclined under the action of an external force, to return to this position after the external force has ceased. However, the severity of the environment withstood by an autonomous sailboat is related to not only the hull but also the overturning moment-producing sail. Therefore, we consider the overturning resistance to describe the ability of autonomous sailboats to resist external disturbances.

Before addressing the overturning resistance, it should first be noted that designers tend to limit the general size (length and displacement) to a specific range, as depicted in Fig. 9. The reasons include consideration of the manufacturing cost, deployment facilities, transportation convenience, and regulatory restrictions (Anthierens et al., 2014; Fernandes et al., 2016; Neal, 2006; Tretow, 2017), where the last reason is the most important. Whether autonomous sailboats belong to the vessel category or a particular buoy is a controversial issue (Alves and Cruz, 2015; Briere, 2008a; Eriksson and Friebe, 2015). However, autonomous sailboats undoubtedly pose a collision risk to passing ships (Anthierens et al., 2014).

Eliasson et al. (2014) and Holzgrafe (2014) revealed that when scaling a design, both the recovery moment and the overturning moment decrease as the scale decreases. However, the rate of decrease in the recovery moment is higher. In other words, autonomous sailboats, which are usually small, require a relatively higher overturning resistance. However, no universally recognized standard applies for overturning resistance. In practice, designers have specified wind speed thresholds to ensure that the platform achieves sufficient resistance to overturning, e.g., Avalon (Giger et al., 2009) was designed to withstand a wind speed of 50 knots and 9-m-high waves near the Irish coast. Other



Notes: * Full capacity; ** sailing mode.

Fig. 5. Reported energy consumption structures of certain platforms.

(a) (b) (c)

Fig. 6. Balanced rig. (a) VAIMOS (Ménage et al., 2014). (b) Spirit of Annapolis (Miller et al., 2013). (c) Avalon (Giger et al., 2009). A more balanced aerodynamic distribution can effectively reduce the energy consumption of the sail system.

(a) (b) (c)

Fig. 7. Self-trimming wings. (a) Maribot Vane (Tretow, 2017). (b) Atlantis (Elkaim, 2006). (c) ASPire (Friebe et al., 2017). The self-trimming sail reduces the load and control frequency requirements when the sail rotates, thus reducing the energy consumption required for control.

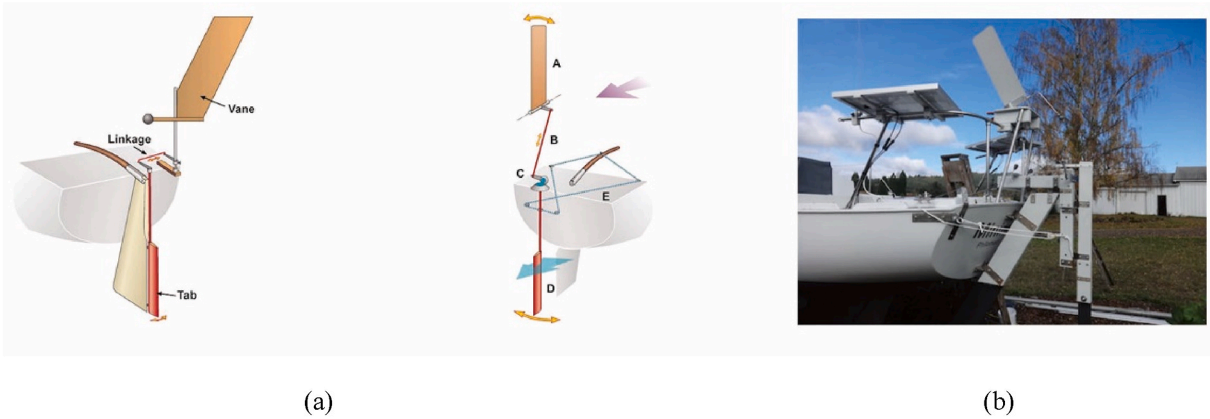


Fig. 8. Self-steering system. (a) Two types of self-steering systems (Offshore Sailor: Windvane self steering). (b) Self-steering system on a sailboat (Self Steering, 2016). When the wind direction changes slightly, the rudder is automatically adjusted without consuming energy.

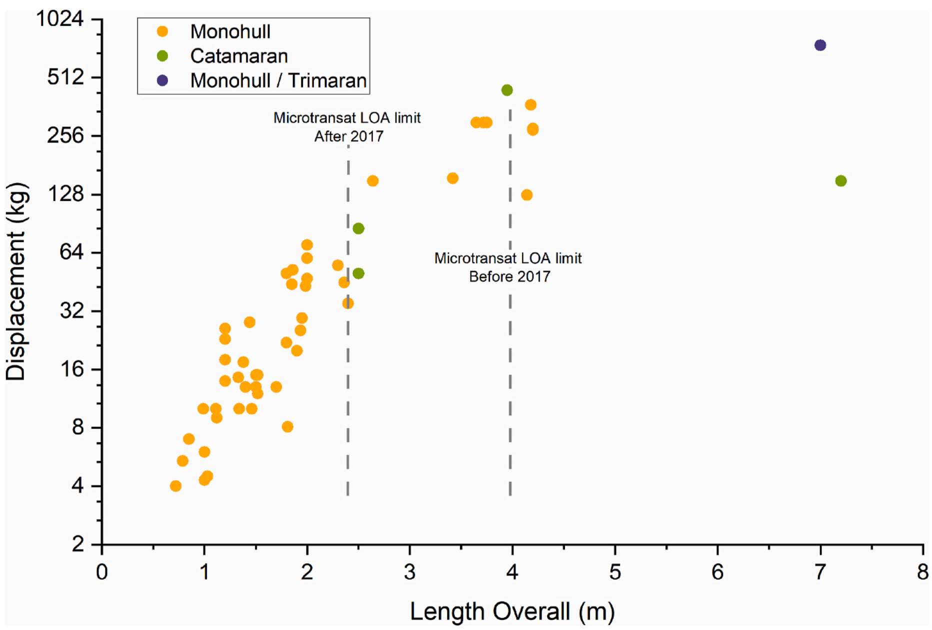


Fig. 9. General size distribution of autonomous sailboats. Statistics show that the general size of autonomous sailboats is usually small. Specific data are listed in Table 2. Note: As the latest news, Saildrone Surveyor completes its first ocean crossing from San Francisco to Hawaii; it is a 22 m long and 12,700 kg monohull platform (Saildrone Surveyor).

suitable configurations have been proposed by adjusting the design based on sea trial results or engineering experience (Sauzé and Neal, 2008a).

Designers have improved the overturning resistance by enhancing the restoring ability produced by the hull and keel. Most designs adopt monohulls (Friebe et al., 2017; Rynne and von Ellenrieder, 2009) instead of multihulls. Although the stability of monohulls is not as high as that of multihulls (Eliasson et al., 2014; Miller et al., 2013), their low inverted stability provides the opportunity for righting with an external disturbance after capsizing (Rynne and von Ellenrieder, 2009). As special cases, a doghouse is placed on the deck to help the sailboat to turn back in case of it rolled over (Naveau et al., 2013); Active self-righting system has been designed for the Datamaran (Fig. 10), which uprights the platform and relies on a swingable sail (PLATFORM — Autonomous

Fig. 10. Active self-righting system of the Datamaran (PLATFORM — Autonomous Marine Systems, 2019). The active self-righting system allows the Datamaran to take full advantage of the good stability of the catamaran and overcome the shortcomings of being unable to upright itself after capsizing.

(a) (b) (c)

Fig. 11. Different strategies to enhance the overturning resistance. (a) The platforms of the United States Naval Academy (USNA) adopt a heavy full keel (Miller et al., 2015b). (b) SailVane applies a low-aspect-ratio sail and deep keel (CUSail | Fleet). (c) The submerged mode greatly enhances the overturning resistance of Submaran S10 (Submaran, 2017).

Marine Systems, 2019). Furthermore, designers often choose crewed sailboats with a good stability as the starting point of design (Fig. 11(a)). For example, Klinck et al. (2009) considered the Laerling boat type, which is a dinghy designed for young beginners, while Ulysse et al. (2019) considered a Paralympic design. In addition, because there is no limitation on roll acceleration based on crew comfort in autonomous sailboat design (Cruz and Alves, 2008a,b; Domínguez-Brito et al., 2016; Sliwka et al., 2011), designers have adopted longer and heavier keels to effectively lower the centre of gravity (Alves and Cruz, 2008; Giger et al., 2009; Neal, 2006). In some instances, extremely long or heavy (or both) keels (as depicted in Fig. 11(b)) provide a self-righting capability—the hull can generate a restoring moment at any heel angle (Baker et al., 2016; Domínguez-Brito et al., 2016; Rynne and Ellenrieder, 2010).

Another commonly employed method is reducing the overturning moment. Sail area reduction is a direct and effective method. Briere (2008a) adopted a 1.5 m^2 sail area instead of the customary 4 m^2 sail area. In the design of Beagle-B, the sail area was reduced by 40% (Neal et al., 2009). Sliwka et al. (2009) also reduced the sail area based on International Monohull Open Class Association (IMOCA) design standards. In addition, lower sails (Stein, 2019) or dual sails (Domínguez-Brito et al., 2016; Du et al., 2018; Sauze et al., 2006; Sauzé and Neal, 2011a) have been adopted to lower the aerodynamic centre of the sail. Due to the wind gradient (ITTC, 2011), a lower aerodynamic centre can notably reduce the overturning moment. SailVane (CUSail | Fleet) uses a stubby wingsail. As a special case, Submaran S10 (Fig. 11(c)) has a retractable wing sail (Submaran, 2017). Under extreme conditions, the sails are brought down, and the platform is submerged and driven by propellers.

2.4. *Sailing speed*

We use the term sailing speed to describe the speed performance of autonomous sailboats under various wind directions and speeds. Although autonomous sailboats are known for their long endurance, the sailing speed remains a vital feature. Compared to the notable efficiency-improving effect in area coverage, the sailing speed greatly facilitates the task of disaster monitoring and water mass tracking. Rathour (2016) pointed out that in the application of oil spill detection, the platform should be faster than 3% of the wind speed at 10 m above the sea surface, which is the drift speed of spilled oil. Furthermore, the sailing speed is the decisive factor in autonomous sailboat passability. Platforms with a poor sailing speed are more likely to be captured by strong currents, with the vessel eventually being stranded and damaged (as indicated in Table 1) (Microtransat-History, 2020). In addition, platforms with slow sailing speeds may have to abandon closer routes to avoid being affected by strong ocean circulation currents, which may severely limit the efficiency of a mission.

Evaluating the sailing speed of a specific design remains a challenging task. First, the sailing speed cannot be characterized by a single value, such as the “average speed”, which has been widely considered in the literature. The speed of an autonomous sailboat is closely related to the wind direction and speed, so the average speed without specified conditions is meaningless. Second, the sailing speed is impossible to evaluate based on the subsystem (hull, keel, and sails) without the other parts designed (Guelfi and Canepa, 2013). For example, a platform with a narrower hull exhibits a lower resistance but a weaker overturning resistance. Designers should adopt a smaller sail to ensure a sufficient overturning resistance, thus limiting the driving force generation.

Therefore, we introduce certain dimensionless numbers that reflect a specific performance aspect to review the existing designs comprehensively and qualitatively (Table 2). The first two dimensionless numbers introduced are the length/displacement ratio (LDR) and length-breadth ratio (L/B) (Eliasson et al., 2014). Generally, longer, slenderer, and lighter hulls exhibit higher speed potential. The sail area/displacement ratio (SA/D) (Sponberg, 2011) describes the power/load ratio of the platform, similar to the power-to-weight ratio of a vehicle. Considering only power conditions, we apply SA/D to both soft and wing sails since Rynne and Von Ellenrieder (2008) noted that the typical lift coefficients of wing and soft sails are very similar. Finally, we introduce the ballast-to-displacement ratio (B/D), which is the percentage of ballast in the total weight, to describe autonomous sailboats, usually by the keel weight/displacement ratio. A high ballast ratio lowers the speed potential but enhances the overturning resistance since the mass stability is usually the primary source of the overturning resistance. The statistics shown in Fig. 12 indicate that designers tend to adopt stubby hulls (catamaran numbers are excluded) with low LDR values. Most SA/D values are lower than 15, corresponding to crewed slow auxiliary sailboats (Sponberg, 2011). The distribution of B/D is considerably dispersed, reflecting that designers do not agree on this parameter.

Research on the sailing speed is limited and mainly focused on evaluating and systematically optimizing the sailing speed.

Velocity prediction programs (VPPs) are reliable tools to predict the speed of a particular design under given external conditions (wind speed and direction) (de Jong et al., 2008; Graf and Bohm, 2005; Kerwin, 1978; ORC VPP - Designer’s version, 2020). As depicted in Fig. 13, the output is usually provided in the form of a polar graph, which can be used as a reference for control strategy formulation and design optimization. Briere (2008b) proposed a four degree-of-freedom (DOF) model to guide control law formulation. Rynne and von Ellenrieder (2010) implemented an Xfoil-based VPP to optimize the design of the self-trimming wing sails of the Maribot Vane. Miller et al. (2018) compared the performance of Viking-style wing sails and traditional soft sails through PCSail, a VPP developed by Martin and Beck (2001). However, An et al. (Unpublished results) noted that existing VPPs typically rely on empirical equation-based modelling and

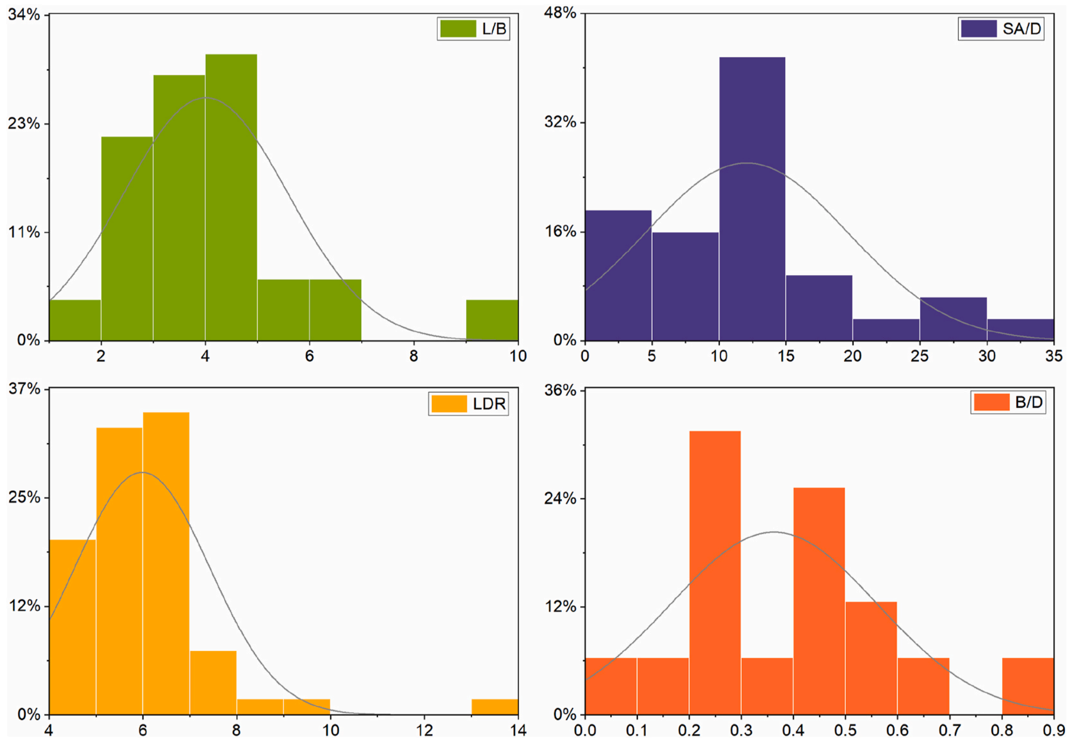


Fig. 12. Distribution of the dimensionless number of existing designs. Statistics indicate that the distributions of LDR, L/B and SA/D are relatively concentrated, while B/D is considerably dispersed.

gradient-based solvers that are unsuitable for the design of autonomous sailboats. Thus, they developed an optimization-based generalized VPP. By using VPP to optimize the sailing speed, Miller et al. (2013) adopted a full-scale tank test to optimize the shape and weight of the keel and bulb, resulting in a speed increase of 15%. Dhomé (2018), and Tretow (2017) adopted the vortex lattice method to model the self-trimming wing and employed a customized MATLAB-based VPP as an evaluator to select reasonable design parameters for the self-trimming wing.

3. Discussion and analysis: factors hindering further performance improvement

Over the past two decades, autonomous sailboats have become effective platforms in multiple marine science missions due to continuous progress. With an appropriate design, proper control, and no unexpected events (disturbance by a passing ship, damage from a serious collision, extreme bad weather, etc.), autonomous sailboats can sail for dozens or even hundreds of days (Cokelet et al., 2015; Cross et al., 2015; De Robertis et al., 2019; Meinig et al., 2015; Vazquez-Cuervo et al., 2019). Also, complete feats such as crossing the Atlantic (SailBuoy - Unmanned Surface Vessel, 2020) and circumnavigating Antarctica (Stein, 2019). However, there are still issues that hinder and restrict the further improvement of the critical performance, mainly due to the insufficient consideration of the coupling among these capacities in the current designs. We now propose a list of emerging challenges that designers should overcome. The list is not intended to be exhaustive but is intended to provide a basis for debate.

3.1. Design customization

In general, most existing designs have been modified based on reference designs, typically remote control (RC) models (<3 m) (Cabrera-Gámez et al., 2014; Neal, 2006; Tranzatto et al., 2015), dinghies (3–5 m) (Anthierens et al., 2014; Ménage et al., 2014), and yachts (>5 m) (Rynne and Ellenrieder, 2010; Sauze et al., 2006), as detailed in Table 3. Reference-based designs are a good starting point, but they introduce inappropriate design considerations: the RC model is usually considered under racing conditions in calmer water, so it provides a poor overturning resistance. In addition, slender hulls may handicap the arrangement of scientific loads. In dinghy design, the weight of the crew is accounted for in the overturning resistance, so a lighter keel (or even a dagger board) is often adopted, which is unsuitable for sea-going autonomous sailboats. Ocean-going yachts exhibit a good overturning resistance, but the simple imitation of reference designs introduces unnecessary constraints. For example, the consideration of crew comfort (Cruz and Alves, 2008a,b; Domínguez-Brito et al., 2016; Sliwka et al., 2011), the flooding angle (Izaguirre-Alza et al., 2008), the port depth, and the class rule ensure the fairness of competitions.

Although the continuous progress has let to improvements in the critical performance, these improvements are not targeted enough. Designers tend to develop a comprehensive platform rather than a task-based platform. However, different tasks are associated with their own capacity requirements. As noted by Hotaling and Kocak (2014), ecosystem researchers are more concerned with the continuity of monitoring, density and frequency of sampling, which requires the platform to achieve better energy self-sufficiency. In contrast, hazard-observing missions require a fast response and a greater overturning resistance. When capacities cannot be improved simultaneously, nontargeted designs are not optimal for the task.

3.2. Trade-off between the sailing speed and the overturning resistance

Crewed sailboats can maintain high performance in various external environments. The overturning and recovering moments can be adjusted by modifying the sail configuration manually and through crew weight hiking. However, there is no available and reliable alternative mechanism for autonomous sailboats (Eriksson and Friebe, 2015; Sauzé and Neal, 2008a; Tretow, 2017). Hence, various external environments must be withstood with a fixed design. In certain tasks, a lack of environmental adaptability can notably degrade the performance of the

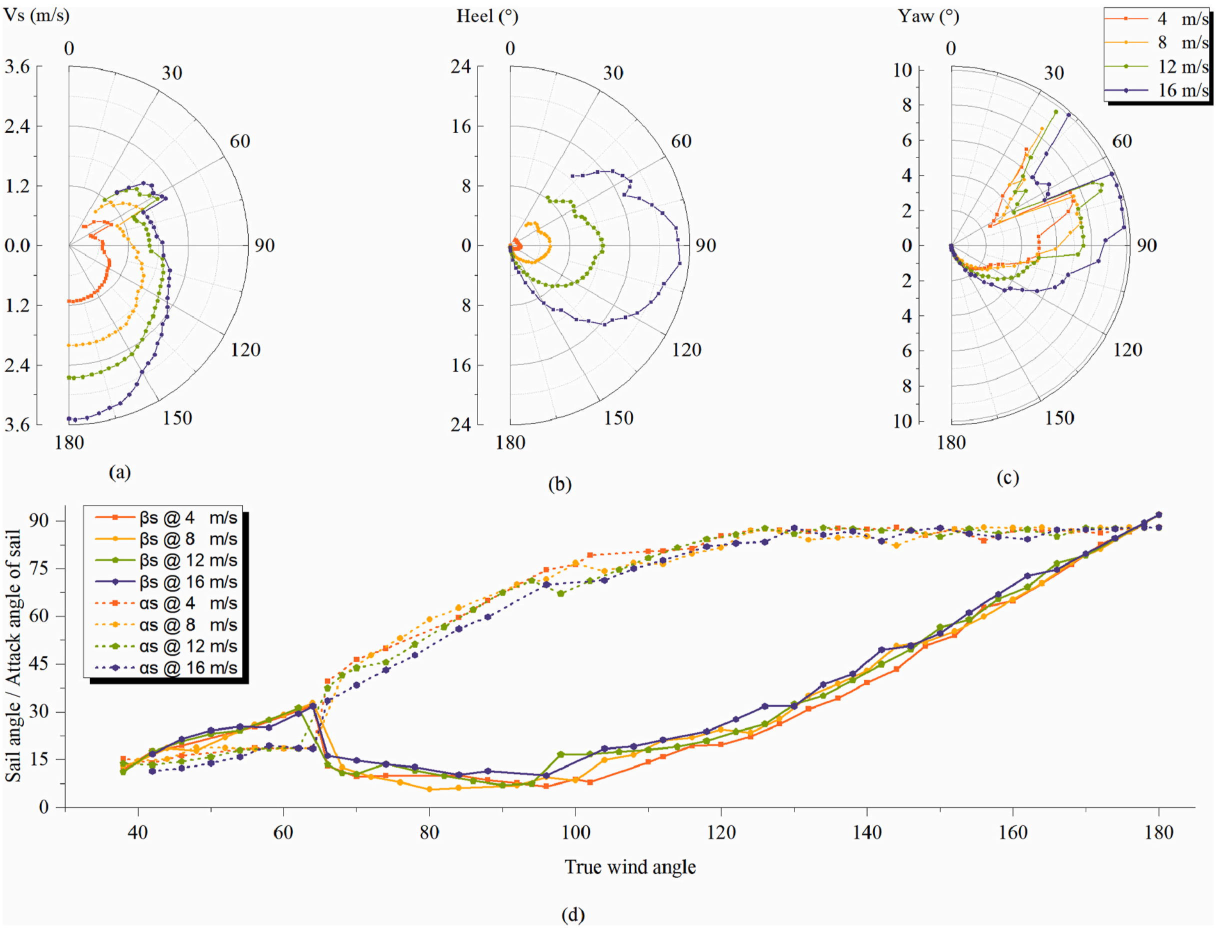


Fig. 13. Demonstration of the prediction results obtained with a VPP (An et al., Unpublished results). A VPP can predict the speed (a), attitude (b,c), and optimal control (d) of a particular design at a given wind speed and direction.

Table 3
Statistics of reported design references. Reference-based designs are a good starting point, but they introduce inappropriate design considerations.

RC model	Dinghy	Yacht
AROO	WASP	Platform in (Abril et al., 1997)
ARC	VAIMOS	That'll do
Fhsailbot	ASPire	Atlantis
Saudade	Erwan 1	Platform in (Augenstein et al., 2017)
Aeolus	AAS	HWT-X1
Platform in (Baker et al., 2016)	Endurance	SOTAB-II
	Beagle-B	Robbe Atlantis
	ASV Roboat	FASt
	Pinta	Platform in (Petres et al., 2011)

platform. For example, when the wind direction and force conditions are adverse in a position-keeping mission, the fixed sail configuration may result in additional energy consumption.

More importantly, as mentioned above, the small general size severely lowers the overturning resistance of autonomous sailboats. Thus, designers have to reduce the sail area (as depicted in Fig. 14) (Briere, 2008a; Neal et al., 2009; Sliwka et al., 2009), adopt heavier keels (Alves and Cruz, 2008; Giger et al., 2009; Neal, 2006), and even design heavy, self-righting hulls (Baker et al., 2016; Domínguez-Brito et al., 2016) to ensure that the platform achieves sufficient overturning resistance in the harshest environments. However, small sails and excess weight reduce the sailing speed in most situations, especially under downwind, moderate conditions (ÇAKICI et al., 2012). A reduction in the sailing speed may seriously affect the mission efficiency, rapid response capability, and regional passability.

Fig. 14. Saildrone with a customized stubby sail (Clemens, 2019; Stein, 2019). Given the conditions in Antarctica, the Saildrone inevitably prioritizes overturning resistance to ensure survivability by adopting a stubby sail rather than the iconic slender sail.

3.3. Design optimization

To date, only a few works related to design optimization have been reported, and most studies are design iterations based on engineering experience or sea trial results, lacking corresponding theoretical guidance (Sauzé and Neal, 2008a). Although engineering studies have been carried out to assess durability, no systematic studies have been conducted on the failure mechanism, force characteristics, and structural optimization of the unique and most vulnerable component of autonomous sailboats, i.e., the sail. In terms of energy self-sufficiency, most energy budgets have been determined based on simple estimates, which sometimes differ from reality (Schröder and Hertel, 2014). Additionally, the proportion of the functional module energy consumption is notable. No comparative conclusion has been proposed regarding the type of main computer and sensors for balancing energy consumption and performance. The sailing speed under downwind and moderate conditions conflicts with the overturning resistance under upwind and harsh conditions. Most existing designs are focused on the latter. Although few studies have optimized the speed performance based on VPPs (Dhomé, 2018; Tretow, 2017), the best trade-off between the sailing speed and overturning resistance has not been determined.

4. Potential solutions: towards more powerful autonomous sailboats

With the ever-increasing practical applications and related research on autonomous sailboats, we expect that over the next decade, autonomous sailboats will become a powerful, indispensable platform for marine science research and may be the answer to existing problems such as underwater cluster communication and virtual mooring. To further enhance the critical performance, the three aspects below should be developed.

4.1. Customized design considering scenarios

The general size, application scenarios, and design purpose of autonomous sailboats are different from those of crewed sailboats. Certain designs are now free from the simple imitation of crewed sailboats, targeted to strengthen the task performance (PLATFORM — Autonomous Marine Systems, 2019; SailBuoy - Unmanned Surface Vessel, 2020; Submaran, 2017; Vazquez-Cuervo et al., 2019). In the future, autonomous sailboats may be designed as dedicated platforms in consideration of mission scenarios.

It is challenging to design a "most suitable" autonomous sailboat for specific mission scenarios because the capability requirements for each specific scenario are complex; thus, the priorities and trade-offs need to be considered appropriately. However, in Table 4, we illustrate the optimal configuration of some meta-scenarios (a specific task may be a complex combination of several meta-scenarios) based on the literature and existing designs. This proposed configuration is expected to help future designers obtain an appropriate scenario-customized design.

Regarding platforms that operate in harsh open seas, the platform should be a wide, heavy monohull equipped with short masts, dual wings, and a deep heavy keel. This configuration provides a notable overturning resistance and high sail and actuator durability. In terms of platforms operating in shallow water, the overturning resistance is not the primary design consideration, but rather the potential risks of collision and scraping are the prominent considerations. Therefore, these platforms should adopt shallow-draft catamaran hulls with short keels, strengthened hulls, and dual rudders. Regarding short-term, highly energy-consuming tasks, energy harvesting is generally insufficient to maintain energy self-sufficiency. Therefore, the design should be based on the capacity of the adopted batteries. These platforms should be wide monohulls with high-energy-density batteries and backup energy. Regarding long-term tasks, energy harvesting is the top priority. A catamaran type with large solar panel-covered decks is preferable; also, dedicated configurations include medium-sized self-trimming wings and a self-steering system. When tasks require downwind performance specialization, the platform should be slender and possess a light catamaran hull equipped with larger soft sails. In contrast, the version with specialized upwind performance should adopt a broader and heavier monohull with higher stability and wing sails and should exhibit a higher lift-drag ratio and a smaller dead zone.

4.2. Adaptive mechanisms for different conditions

At present, certain autonomous sailboats include mechanisms to offset extreme conditions, such as the Submaran's retractable wing sails and the Datamaran's active self-righting system. However, retracted sails sacrifice all the driving force; the active self-righting system represents an emergency measure rather than an adaptation to different environments. In the future, mechanisms from related fields may be applied to autonomous sailboats to enable the platform to adapt to both breezes and gales with minimal loss in the driving force and thereby fundamentally alleviate or even solve the contradiction between the overturning resistance and the sailing speed. The mechanism is described below, and the pros and cons for autonomous sailboats are listed in Table 5.

The first promising type of technology involves reefable sails. These sails can be dynamically adjusted according to the environment and maximize the driving force while ensuring a suitable overturning resistance. Junk rigs (Hasler et al., 2004), as depicted in Fig. 15(a) are sails with a long history, and their mast independence makes them very suitable for automatic adjustment. The transition rig (Dryden, 2004) is a bionic foldable sail (Fig. 15(b)). A hinged mast allows the sail to modify its geometry according to the wind, similar to a bird adjusting its wing shape. In green shipping, telescoping retractable sails, as depicted in Fig. 15(c) are used to assist commercial ship propulsion (Oceanbird; Ouchi, 2009). Retractable sails satisfy energy-saving and emission reduction needs while ensuring safety in bad weather and providing trafficability when passing bridges. Inflatable wing sails (Fig. 16) were designed by the IWS company (Inflated Wing Sails, 2018). The sail area and aerodynamic shape are adjusted by continuously operating interior fans.

Adjustable variant sails represent another mechanism that provides adaptability to changing environments. When the magnus sail (Fig. 17 (a)) is driven to rotate, pressure differences are formed, and a driving force is generated (the magnus effect (Magnus effect - Wikipedia, 2021)). By designating the rotation speed, ships with magnus sails maintain smaller roll angles in a storm (Nuttall and Kaitu'u, 2016). Sky

Table 4
Preferable configurations for meta-scenarios.

Scenario	Key capability	Hull	Sail	Keel	Additional
Harsh open sea	Overturning resistance	Wide monohull	Short, small area	Deep, heavy	Dual sails
Gentle shallow waters	Structural durability	Catamaran with a shallow draft	–	Short	Dual rudders and hull strengthening
Short-term, high energy consumption	Energy carrying	High-capacity monohull	Large area	–	Backup fuel cell
Long-term, medium energy consumption	Energy harvesting	Catamaran with a large deck area	Medium area	–	Self-trimming sails and self-steering system
Upwind performance specialization	Upwind speed	Catamaran with slender demihulls	Large area	Light	Soft sails
Downwind performance specialization	Downwind speed	Monohull with medium L/D	Large area,	Deep, heavy	Wing sails

Note: Preferable configurations are for the best performance of the meta-scenarios, a specific task may be a complex combination of several meta scenarios.

Table 5
Pros and Cons of the environment-adaptive mechanisms.

Types	Mechanism	Pros	Cons	References
Reefable sails	Junk rig	• Provide driving force after partial damage • Good downwind performance • Low energy consumption	• The mast cannot be stowed • Poor upwind performance	Hasler et al. (2004)
	Bionic foldable sail	• Lightweight • Low energy consumption	• Complicated in structure	Dryden (2004)
	Telescoping retractable sail	• Negligible performance loss	• Complicated in structure • Heavy	(Oceanbird.; Ouchi, 2009)
	Inflatable wing sail	• Lightweight	• Energy consuming • Difficult to maintain the profile	Inflated Wing Sails (2018)
Adjustable variant sails	Magnus sail	• Force generated can be adjusted precisely • Good performance in cross wind	• Energy consuming • Poor upwind and downwind performance	(Bergeson et al., 1981; Bergeson and Greenwald, 1985, pp. 1979–1985; Nuttall and Kaitu'u, 2016)
	Skysail	• Almost eliminate the overturning moment • High utilization of wind energy.	• Complicated in control • Larger dead zone	(Bigi et al., 2015; ITTC, 2011; Naaijen and Koster, 2007; SkySails Yacht, 2021)
Stabilizers	Canting keel	• Generated recovery moment can be precisely adjusted	• Energy consuming • Require extra dagger boards	(Claughton and Oliver, 2004; Hobbs and Manganelli, 2007; Tier et al., 2006)
	Passive hydrofoil	• No energy consumption • Lightweight	• Easily scratched • Complicated design	(Aygor and others, 2017; Labi and others, 2019; Official website of the Vendée Globe, 2021)

sails (Fig. 17(b)) are controlled paragliders, and their curvature and shape can be adjusted via bridle lines connected to a controller. Due to the wind gradient (ITTC, 2011), skysails operating at high altitudes can produce a higher driving force (SkySails Yacht, 2021). More importantly, the vertical height of the towing point is low, so the overturning moment generated can be almost ignored (Bigi et al., 2015; Naaijen and Koster, 2007). Sky sails can also be applied to generate power directly, but that goes beyond our definition of being directly driven by wind energy. For details, please refer to (Costello et al., 2015; Fritz, 2013).

The last type of promising technology is stabilizers, including the canting keel and passive hydrofoil (Fig. 18), which can provide extra stability according to the external environment. Canting keels (Hobbs and Manganelli, 2007) provide additional stability by swinging windward (Claughton and Oliver, 2004). With canting keels, sufficient overturning resistance is provided under a lighter ballast, which can improve the sailing speed of autonomous sailboats. Passive hydrofoil is a well-performing wing adopted by ocean-going yachts (Official website of the Vendée Globe, 2021), usually in the form of a Dali moustache-shaped foil, chistera foil, or dynamic stability system (DSS) foil (Labi and others, 2019). When a sailboat heels, the passive hydrofoil becomes submerged and generates lift, which provides a recovery moment and slightly lifts the hull. The hydrofoil can notably improve the sailing speed and overturning resistance performance under gale conditions (Aygor and others, 2017; Official website of the Vendée Globe, 2021) because the generated lift is proportional to the square of the speed. However, the passive hydrofoil yields an indirect effect (by improving the stability, supporting a giant sail and, therefore, improving the sailing speed). The design of a hydrofoil with more positive effects than the resultant additional resistance is the core topic.

4.3. Design optimization under the simulation-based framework

Although the mission requirements and design considerations of autonomous sailboats are different from those of crewed sailboats (Keuning and Sonnenberg, 1998), the advanced design method for crewed sailboats is of reference value. In the future, these design methods will be more widely applied in the design of autonomous sailboats.

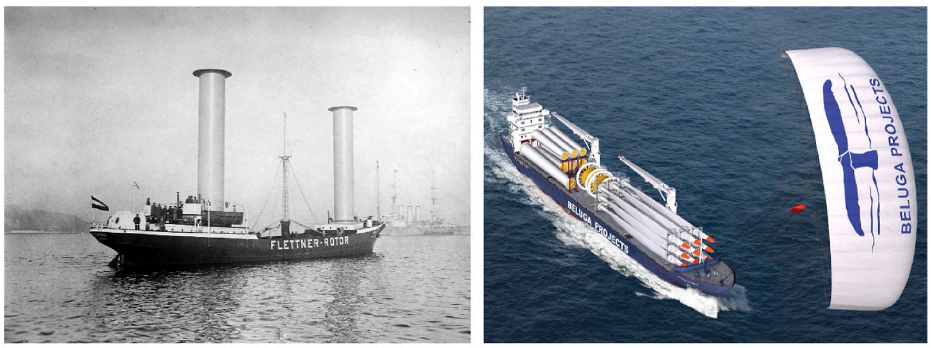
Parametric modelling technology (Bole, 1997; Hochkirch et al., 2002) establishes a one-to-one mapping between design parameters and 3D models. By changing the design parameters, the parametric model is easily adjusted, with smoothness constraints satisfied. Parametric modelling technology enables convenient design space exploration of different task requirements, working environments, and layout constraints. Moreover, it facilitates further research on the influence of design parameters on performance.

"Designing a yacht, in particular its hull geometry and appendages is a process of creativity, skill, experience, and art (Harries et al., 2001)".

(a) (b) (c)

Fig. 15. Examples of reefable sails. (a) A damaged junk rig remains operable (What are the advantages and disadvantages of a junk rig?). (b) Transition rig and its folding mechanism (Dryden, 2004). (c) Design sketch of telescoping retractable sails (Oceanbird).

Fig. 16. Inflatable wing (Inflated Wing Sails, 2018). When the sail area of the inflatable sail requires modification, sail units deflate, the mast is lowered, and the deflated sail is placed in the nest.



(a) (b)

Fig. 17. Adjustable variant sails. (a) Buckau 1924, the first ship with a magnus sail (Sclavounos, 2020). (b) The skysail (SkySails Yacht, 2021).

Fig. 18. Safran IMOCA 60 equipped with a canting keel and passive hydrofoil (IMOCA Globe Series, 2016; Stability and foils on the new IMOCA, the operating principles, 2017).

Regarding the task-oriented ad hoc design of autonomous sailboats, the difficulty of reliably estimating the performance in advance results in the difficulty of establishing the initial design. Simulation-driven design (SBD) (Sellgren, 1999) can transform the general design of autonomous sailboats into an optimization problem based on a computational fluid dynamics (CFD) design evaluation. In crewed sailboat design, the Wide Light Project (Prince and Claughton, 2016) has demonstrated that commercial CFD software can capture the typical effect of design parameters on the performance without requiring an excessive grid density. Although the SBD technique may not completely replace an experienced designer, the approach provides a sufficiently good design and design evaluation methods without expensive model tests considering ad hoc design tasks.

Optimization studies focused on autonomous sailboats (Dhomé, 2018; Tretow, 2017) often regard speed as the only optimization objective. In the future, the multidisciplinary design optimization (MDO) method may be introduced to consider multiple critical performances simultaneously. Thus, the coupling between design parameters and capabilities can be fully considered to obtain an optimal design given specified requirements and scenarios.

However, in the above framework, prioritizing as few design parameters as possible to simplify the parametric model, balancing the accuracy and computational complexity, and selecting multidisciplinary criteria to reasonably capture the coupling relationship among capacities constitute high-priority research topics.

5. Conclusions

After 20 years of development, autonomous sailboats have become a powerful tool for marine science from the concept platform in the laboratory. This paper provides a comprehensive summary of existing designs from the perspective of performance, discusses fruitful advances in enhancing the structural durability, energy self-sufficiency, overturning resistance, and sailing speed and provides insights regarding the design logic. According to the statistics and analysis of the existing designs, this paper reveals three aspects that constrain further performance improvements: inadequate consideration is given to task scenarios, trade-offs between the sailing speed and the overturning resistance are insufficiently addressed, and the design and optimization framework is still far from complete.

Regarding the future of these platforms, the authors introduced technologies in related fields that can be used as potential solutions. By adopting a scenario-specific design, adaptive mechanisms for different conditions, and simulation-based optimization, breakthrough improvements in the performance of autonomous sailboats will be made, and these platforms will play a more critical role in marine science activities.

CRediT authorship contribution statement

Yang An: Conceptualization, Writing (Original Draft), Investigation and Visualization; Jiancheng Yu: Conceptualization, Supervision, Project Administration and Writing (Review and Editing); Jin Zhang: Conceptualization and Writing (Review and Editing).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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