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Survey on Autonomous Surface Vessels: Part II - Categorization of 60 Prototypes and Future Applications

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Abstract. Autonomous Surface Vessels (ASVs) have been developed for more than 20 years. Many ASV projects have been successfully realized, and as many are still under development. In literature there is a lack of research on the different applications and suitable environments for the deployment of ASV.
Recently, a detailed definition and categorization of autonomy levels for ASVs has been proposed based on the characteristics of ASVs and existing classifications of autonomy. With this innovative autonomy level classification, this paper presents an extensive overview of existing ASV prototypes. The tendency and possible future developments of ASVs are analyzed according to the divisions obtained.

Keywords: Autonomous Surface Vessels; Autonomy level; ASV projects; ASV prototypes

1 Introduction

Autonomous Surface Vessels (ASVs) have been involved in numerous projects since the 1990s. The goal is typically to achieve fully autonomous navigation. The concept of autonomous surface vessel is well known at an academic level, and is now gaining attention also in full scale vessel development for the container and bulk sectors [8, 51, 67, 68].

In literature, a lack of research about current development of ASVs has been observed. Therefore, in this paper, we present an overview of existing projects to gain knowledge about the emerging concepts and techniques that have been applied in ASV research. The tendency and possible future developments of ASVs are analyzed according to the overview.

The remainder of this paper is organized as follows. An overview of existing ASVs found in literature is presented in Section 2. Detail informations about the ASV prototypes are introduced in Section 3 according to their autonomy levels. The tendency and unknown future developments of ASVs are analyzed according to the divisions in Section 4. Conclusions are discussed in Section 5.

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2 Overview of existing ASV projects

To gain insight into the ASVs prototypes, the existing projects are analyzed in this section. Different components of the ASVs are compared to obtain a full picture of the current technologies used in ASV research.

Existing ASV prototypes (includes those under development) that have been mentioned in literature are presented in Table 1, Table 2 and Table 3. We review the ASV prototypes based on the components as discussed in [61]. An ASV is divided in four control subsystems: engine system, communication system, sensors and navigation, guidance and control (NGC) system. The common element that supports all the those components is the hull. The dimensions, scope and the deployment year of the ASVs are also presented in the tables.

Most existing ASVs are scaled models. Mainly two types of hull are used, i.e., single hull and double hull (as catamaran). The main solution in the engine compartment is the adoption of electric motors together with batteries. If the vessel should endure in the operations, solar panels or methanol fuel cells are implied. Another common option, which requires higher level of navigation control, is using sails as a propulsion system (Project 11, 17, 18, 19, etc.). Several projects also considered heavy fuel treatment systems, such as Project 51.

Focusing on the NGC system, almost all the prototypes rely on a path following control, coupled with compass, IMU and GPS. The most advanced prototypes are able to detect obstacles, with stereo cameras, LiDAR or ARPA, and recompute the route in order to avoid them. Some vessels have the function of dynamic positioning, such as as Project 3, 20, 21, etc.

The communication system in the prototypes is arranged for the information exchange between vessel and controllers, or to take remote control of the vessels or with other agents. Wi-Fi and Radio are two main methods.

Detailed descriptions regarding the projects can be found in Section 3, structured according to the autonomy level they achieved.

3 Autonomy levels of ASV prototypes

3.1 Autonomy level categorization for ASVs

In [61], we proposed an innovative autonomy levels categorization based on the characteristics of ASVs and existing classification of autonomy. As shown in Table 4, the categorization gives an overall autonomy level of a vessel by analyzing the automated sub-systems: Decision, Actions, Exceptions, and Cooperation. The Decision, Actions and Exceptions subsystems are assessed by means of a scale from 1 to 10, where 1 is completely human operated and 10 is fully autonomous. The last subsystem, Cooperative, is evaluated from 1 to 5 based on the number of agents it is able to communicate with. After evaluating the subsystems, an overall autonomy level of the entire system can be determined. the overall autonomy level ranged from 0-10. In each autonomy level, sub-levels are designed consider different combinations of the four subsystems. Subsequently, these existing prototypes are classified based on the autonomy level.

Table 1. Overview of ASV projects – Part 1

No.	Prototype		Components																Dimensions			Scope		Year	Ref.
	Name	Institution	Hull		Engine			Fuel			Steering			NGC			Comm.	Sensors	L	W	H	Geo.	App.		
			Si	Ca	EM	Sa	CE	Ba	FF	So	Dp	Pr	Ru	PF	OA	DP			(m)	(m)	(m)				
1	Proteus	Marine Advanced Research, Inc.		●	2			†			▲				Human				30.48	15.24	-	Off-shore	Military	2007	[1]
2	ASV MUN	MUN (Uni.)		●	2			†			▲						Radio	GPS, AHRS	1.5	1	0.5	On-shore	Scientific	2013	[43]
3	ASV SMU	SMU (Uni.)		●	2			†				▲		√		√	Wi-Fi	GPS	2.7	1.48	0.36	On-shore	Scientific	2008	[72]
4	Seabax	TU Delft (Uni)	●		4			†				▲			QR-codes		Wi-Fi	GPS, IMU, Camera, accelerometer, gyroscope, rpm sensors	1.4	0.28	0.38	Off-shore, Waterways[1]	Commercial	2015	[22, 53]
5	Rolls Royce ASV	Rolls Royce	●																60	-	-	On-shore	Commercial	2020	[42, 58]
6	ASV Prototype	UNIVPM (Uni)	●		1		1	†	G			▲			Set of commands		Wi-Fi	GPS, IMU, Camera	3.05	1.4	-	On-shore	Scientific	2015	[19]
7	Circe	Olin College (Uni.)		●	2			†						√				GPS, Compass	1.98	1.37	-	Inland[2]	Recreational	2007	[38]
8	ALANIS	CNR-ISSIA	●				1		G			▲		√			Radio	GPS, Compass, Clinometer	4.5	2.2	-	On-shore	Scientific	2009	[9, 11]
9	ERON	Frederick (Uni.)	●		4			†			▲			√				GPS, Compass, Accelerometer	2.86	0.7	-	On-shore	Scientific	2016	[24, 25]
10	CaRoLIME	HTWG (Uni.)		●	2			†			▲							GPS, Compass, IMU	2.5	1.2	-	Inland	Scientific	2012	[73]
11	ENSIETA	ENSIETA (Uni.)	●			2		†					▲		Heading following		Radio	GPS, Wind, Compass	1.2	-	-	On-shore	Recreational	2009	[2, 63]
12	DELFIM	ISR-Lisboa		●	2			†			▲			√			Radio	GPS, Acoustic transducer, Sonar	3.5	2	-	On-shore	Scientific	2006	[3]
13	MARV	SCU (Uni.)		●	2			†				▲		√			Wi-Fi	GPS, Sonar	1.37	2	0.25	Inland	Scientific	2016	[5]
14	WAM-V	UC Berkeley (Uni.)		●	2			†				▲		√			Radio, Cellular	GPS, IMU, Camera, Hydrophone	4.3	2.1	1.23	Off-shore	Military	2012	[54, 15]
15	SCOAP	URI (Uni.)		●	2			†	D		▲			√			Radio, Satellite	GPS, AIS, ADCP, winched CTD, Weather station	11	5	-	On-shore	Scientific	2014	[18]
16	Zarco	U.Porto (Uni.)		●	2			†			▲			√			Wi-Fi	2x DGPS, Compass, Sensor	1.5	-	-	Waterways	Scientific	2007	[20]
17	A-TIRMA G2	ULPGC (Uni.)	●			2							▲						2	0.48		Off-shore	Recreational	2015	[26]
18	A-TIRMA G1	ULPGC (Uni.)	●			2		†					▲	√			Radio	GPS, Compass, Wind, Inclinometers	1	0.245	1.6	On-shore	Recreational	2014	[10]
19	SailBuoy	MET Norway	●			1		†					▲	√			Satellite	GPS, Temperature, Oxygen Sensor	2	-	-	Off-shore	Scientific	2012	[32]
20	OASIS	Emergent Space Technologies, Inc.	●		1			†		†			▲	√		√	Radio, Satellite	GPS, Compass, Inclinometers, IMU, Weather	5.48	1.5	1.82	Off-shore	Scientific	2005	[35]

Hull: Si: Single, Ca: Catamaran
Fuel: Ba: Battery, FF: Fossil Fuel, So: Solar panel, D: Diesel, G: Gasoline
NGC: PF: Path following, OA: Obstacle Avoidance, DP: Dynamic Positioning
Institution: abbreviation with (Uni) are universities
Engine: EM: Electric Motor, Sa: Sail, CE: Combustion engine
Steering: Dp: Differential propeller, Pr: Propeller Rotation, Ru: Rudder
Scope: Geo.: Geographic, App.: Application

[1] 'Waterways' denotes inland waterways (rivers and canals).
[2] 'Inland' denotes lakes.

Table 2. Overview of ASV projects – Part 2

No.	Prototype		Components																Dimensions (m)			Scope		Year	Ref.
	Name	Institution	Hull		Engine			Fuel			Steering			NGC			Comm.	Sensors	L	W	H	Geo.	App.		
			Si	Ca	EM	Sa	CE	Ba	FF	So	Dp	Pr	Ru	PF	OA	DP			(m)	(m)	(m)				
21	WaveGlider	Liquid Robotics	●	●	1			†		†			▲	√		√	Radio, Satellite	GPS, Compass, Hydrophone	3.05	-	-	Off-shore	Scientific	2005	[36]
22	Lizhbeth	ETH Zurich (Uni.)			2			†			▲			√			Wi-Fi	GPS, Compass, Winched probe, Sonar	2.5	1.8	-	Inland	Scientific	2012	[37]
23	Artemis	MIT (Uni.)	●		1			†					▲	√			Radio	DGPS, Compass, Depth sounder	1.4	0.4	-	Inland	Scientific	1993	[57, 46]
24	ACES	MIT (Uni.)		●			1	†	G				▲	√			Radio	DGSP	1.9	1.3	-	Inland	Scientific	1997	[46]
25	Swordfish	ISEP (Uni.)		●	2			†			▲			√			Radio, Wi-Fi, Cellular	GPS, Compass, IMU, Camera,	4.5	2.2	0.5	On-shore	Scientific	2007	[29]
26	ASV	RMUTT (Uni.)	●				1	†	G			▲		√			Cellular	GPS, IMU, Sonar	3.5	1.52	0.6	Inland	Scientific	2015	[56]
27	N-Boat	UFRN(Uni)	●			2		†					▲	√			Wi-Fi	GPS, Wind	0.9	-	-	Inland	Scientific	2015	[40, 59]
28	Proto 1	Aberystwyth (Uni.)	●			1		†					▲	Heading following				GPS, Compass, Wind	1.5	-	-	Inland	Scientific	2005	[60]
29	Proto 2	Aberystwyth (Uni.)	●			2		†					▲	Heading following				GPS, Compass, Wind	1.5	-	-	Inland	Scientific	2006	[60]
30	ASV ROBOAT[3]	INNOC	●			2		†		†			▲				Wi-Fi, Cellular, Satellite	GPS, compass	3.72	-	-	Off-shore	Scientific	2012	[65]
31	WAM-V USV16	FAU (Uni.)		●	2			†				▲		√			Radio	GPS, IMU, Sonar	4.05	2.44	-	Inland	Scientific	2016	[71]
32	VAIMOS	IFREMER	●			1		†		†			▲	√			Wi-Fi, Satellite	GPS, Compass, Wind	3.65	-	-	On-shore	Scientific	2013	[6]
33	CRW	CMU (Uni.)		●	1			†				▲		√			Cellular, Wi-Fi, Bluetooth	Phone (GPS, Compass, Gyroscope, Camera), Water sampler	1.5	-	-	Inland	Scientific	2014	[70]
34	USNA	USNA (Uni.)	●			1		†		†			▲	√	√		Wi-Fi	GPS, Compass, Wind, Ultrasonic Range Finder	2	0.3	-	On-shore	Recreational	2010	[50]
35	IMOCA 60		●			2	1	†					▲	√			Satellite	GPS, AIS, ARPA	18		-	Off-shore	Recreational	2000	[62]
36	Tito Neri	TU Delft (Uni.)			3			†				▲				√	Wi-Fi	Webcam, two sensors for azimuth thruster speeds	0.97	0.32	0.12	Off-shore, Waterways	Scientific	1993	[23, 53]
37	SeaWASP	SCU (Uni.)	Submerged Catamaran		2			†			▲			√			Wi-Fi	GPS, Velocimetry, AHRS, Sonar	1.5	1.5	-	Waterways	Scientific	2008	[7, 45]
38	Charlie USV	CNR-ISSIA		●	2			†		†			▲	Vessel following capabilities			Wi-Fi, Radio	GPS, Compass	2.4	1.7	0.6	On-shore	Scientific	2004	[9, 12, 13, 14]
39	Electric boat	Northrop Grumman Corporation	●		1			†					▲	√	√		Radio	GPS, Compass, IMU, 6xCameras	4	-	-	Waterways	Scientific	2004	[64]
40	Rolls Royce ASV 2	Rolls Royce	●					†											60	-	-	Off-shore	Commercial	2030	[42, 58]

[3] Prototype 30 has Methanol Fuel Cell as fuel.
[4] Prototype 41 has Methanol Fuel Cell as fuel.

Table 3. Overview of ASV projects – Part 3

No.	Prototype		Components																Dimensions (m)			Scope		Year	Ref.
	Name	Institution	Hull		Engine			Fuel			Steering			NGC			Comm.	Sensors	L	W	H	Geo.	App.		
			Si	Ca	EM	Sa	CE	Ba	FF	So	Dp	Pr	Ru	PF	OA	DP			(m)	(m)	(m)				
41	AVALON[4]	ETH Zurich (Uni.)	●			1		†		†			▲	√			Satellite	GPS, IMU, Wind, AIS	3.95	0.7	0.4	Off-shore	Recreational	2009	[33]
42	MAINAMI	MARITEC	●		2		1	†	D				▲	Path and AUV following			Wi-Fi, Radio, Inmarsat	GPS, Camera, Compass, ADCP, Acoustic device	6	2.6	3.2	Off-shore	Scientific	2015	[52]
43	iNav-I	WUT (Uni)	●		1			†				▲		√			Radio	GPS, IMU, RTK, Camera, MMW, compass, Wind	4.0	1.5	0.6	Inland, Waterways	Scientific	2014-[5]	[75]
44	ROAZ	ISEP (Uni.)		●	2			†			▲			√			Wi-Fi	GPS, Compass, IMU, Video Camera	1.5	1	0.52	On-shore	Scientific	2006	[28, 48, 49]
45	ROAZ II	ISEP (Uni.)		●	2			†				▲		Path and target following			Wi-Fi	GPS, IMU, Camera	4.5	2.2	0.5	On-shore	Scientific	2007	[49]
46	SCOUT	MIT (Uni.)	Single Kayak		1			†				▲		√			Wi-Fi, Radio	GPS, Compass	3	-	-	Inland	Scientific	2004	[21]
47	Challenger 2000	SPAWAR	●				1					▲		√	√			GPS, ENC, Radar, Stereo vision, Monocular vision	6	2.4	-	On-shore	Military	2006	[41]
48	WUT-1	WUT (Uni)	●		1			1				▲		√	√		Wi-Fi	GPS, Lidar, Radar, INS, Fathometer, Camera	3.2	0.65	0.5	Inland, Waterways	Scientific	2014-	[17, 44]
49	ReVOLT	DNV GL	●		2			†				▲							60	14.5	12.18	Off-shore	Commercial	2018	[8, 67, 68]
50	CS Saucer	NTNU (Uni.)	Spherical		3			†				▲		√	√	√	Wi-Fi	Accelerometer, Lidar	0.548	0.548		Inland	Scientific	2015	[69, 39]
51	MUNIN	MUNIN Consortium	●					†	D					√	√		Satellite	GPS, Radar, AIS, Weather	-	-	-	Off-shore	Commercial	2016	[51]
52	ASAROME[6]	ISIR	●			2		†		†			▲	√	√		Wi-Fi	GPS, IMU, 360° Camera, Sonar, Hydrophones, Windvane, Water Speed	3.5	-	-	Inland	Scientific	2015	[55]
53	PROPAGATOR 2	UF (Uni.)		●		2		†				▲		√	√		Radio, Wi-Fi	GPS, Camera, Lidar	1.8			Inland	Recreational	2015	[30, 31]
54	PROPAGATOR 1	UF (Uni.)		●	3			†			▲			√	√		Wi-Fi	GPS, IMU, Camera, Lidar, Infrared Thermometer	1.8	0.76	0.7	Inland	Recreational	2013	[34]
55	Rolls Royce ASV 3	Rolls Royce	●																60	-	-	Off-shore	Commercial	2035	[42, 58]
56	Delfia-1	TU Delft (Uni.)		●	2			†				▲		√	√	√	Radio, Wi-Fi	Camera, 6 infrared sensors, 8 ultra-sonic sensors	0.375	0.184	0.11	Waterways, port	Commercial	2015-	[53, 66]
57	Delfia-1 Star	TU Delft (Uni.)		●	2			†				▲		√	√	√	Radio, Wi-Fi	Camera, 6 infrared sensors, 8 ultra-sonic sensors	0.375	0.184	0.11	Waterways, port	Commercial	2016-	[53]
58	ROBOAT AMS	MIT (Uni.)		●															3	2.5	-	Waterways	Civil	2017-	[4]
59	Barlavento	CINAV	●			2							▲	√			Radio	GPS, Compass, Anemometer	2	0.2	-	On-shore	Recreational	2017	[27]
60	AutoCAT	MIT (Uni.)		●	2			†			▲							GPS	1.8	1.3	-	Inland	Scientific	2000	[47]

[5] "2014-" means the project starts from 2014.
[6] Prototype 52 has Wind Turbine.

Table 4. Autonomy levels for ASVs [61]

	Autonomy Level	**Sub level**	**Decision**	**Action**	**Exception**	**Cooperation**
Human is alone	**0**	**1**	1	1	1	1
Human is helped by systems	**1**	**1**	1	1	1	2
	1	**2**	2-4	1	1	1
	1	**3**	1	2-4	1	1
	1	**4**	1	1	2	1
Human is helped by the systems and other agents	**2**	**1**	2-4	1	1	3-5
	2	**2**	1	2-4	1	3-5
	2	**3**	1	1	2	3-5
	2	**4**	1	1	1	3-5
Autonomous path following vessel	**3**	**1**	1	5	1	1
	3	**2**	1	5	1	2
	3	**3**	2-4	5	1	1
	3	**4**	2-4	5	1	2
	3	**5**	2-4	5	1	3-5
	3	**6**	2-4	5	2	2
	3	**7**	2-4	5	2	3-5
Autonomous trajectory tracking vessel	**4**	**1**	1	6	1	1-2
	4	**2**	1	6	1	3-5
	4	**3**	2-4	6	1	1
	4	**4**	2-4	6	1	2
	4	**5**	2-4	6	1	3-5
	4	**6**	2-4	6	2	2
	4	**7**	2-4	6	2	3-5
Human in the loop	**5**	**1**	5-6	5	1	1
	5	**2**	5-6	5	2	2
	5	**3**	5-6	5	2	3-5
	5	**4**	5-6	5	3	2
	5	**5**	5-6	5	3	3-5
	5	**6**	5-6	5	4	2
	5	**7**	5-6	5	4	3-5
	5	**8**	5-6	5	5-6	2
	5	**9**	5-6	5	5-6	3-5
	5	**10**	5-6	6	1	1
	5	**11**	5-6	6	2	2
	5	**12**	5-6	6	2	3-5
	5	**13**	5-6	6	3	2
	5	**14**	5-6	6	3	3-5
	5	**15**	5-6	6	4	2
	5	**16**	5-6	6	4	3-5
	5	**17**	5-6	6	5-6	2
	5	**18**	5-6	6	5-6	3-5
Human supervise the decisions making system	**6**	**1**	7-8	5	1	1
	6	**2**	7-8	5	2	2
	6	**3**	7-8	5	2	3-5
	6	**4**	7-8	5	3	2
	6	**5**	7-8	5	3	3-5
	6	**6**	7-8	5	4	2
	6	**7**	7-8	5	4	3-5
	6	**8**	7-8	5	5-6	2
	6	**9**	7-8	5	5-6	3-5
	6	**10**	7-8	6	1	1
	6	**11**	7-8	6	2	2
	6	**12**	7-8	6	2	3-5
	6	**13**	7-8	6	3	2
	6	**14**	7-8	6	3	3-5
	6	**15**	7-8	6	4	2
	6	**16**	7-8	6	4	3-5
	6	**17**	7-8	6	5-6	2
	6	**18**	7-8	6	5-6	3-5
Human supervise the actions making system	**7**	**1**	5-6	7-8	1	1
	7	**2**	5-6	7-8	1	2
	7	**3**	5-6	7-8	1	3-5
	7	**4**	5-6	7-8	2	2
	7	**5**	5-6	7-8	2	3-5
	7	**6**	5-6	7-8	3	2
	7	**7**	5-6	7-8	3	3-5
	7	**8**	5-6	7-8	4	2
	7	**9**	5-6	7-8	4	3-5
	7	**10**	5-6	7-8	5-6	2
	7	**11**	5-6	7-8	5-6	3-5
Human supervise the exceptions	**8**	**1**	5-6	5	7-8	2
	8	**2**	5-6	5	7-8	3-5
	8	**3**	5-6	6	7-8	2
	8	**4**	5-6	6	7-8	3-5
Human supervise actions, decision and exceptions	**9**	**1**	7-8	7-8	7-8	2
	9	**2**	7-8	7-8	7-8	3-5
Fully autonomous	**10**	**1**	9-10	9-10	9-10	2
	10	**2**	9-10	9-10	9-10	3-5

3.2 Autonomy levels of ASV prototypes

Table 5 shows the score of each subsystem found on board and the overall autonomy level of each prototype. In the last column, the number before the decimal point is the main autonomy level the ASV belongs to, while the number after the decimal point is the sub-level. For example, Level 3.2 means the ASV prototype belongs to sub-level 2 in autonomy level 3.

The most populated main autonomy level is Level 3, which represent an autonomous path following vessel. The first step is to set up an ASV able to follow a predefined path, established using coordinates as the keypoints. The sublevel 3.1 represent the ability to only engage an autopilot, sublevel 3.2 implement the ability to communicate with a remote control, sublevel 3.5 has an updated decision making system and is able to communicate with other vessels, while sublevel 3.6 is an improvement in the exceptions handling system. Level 9 is the highest level that existing prototypes achieve. The sublevel 9.1 has 4 prototypes able to autonomously set up a route, follow it and avoid the obstacles on the way. The limitation is the ability to communicate only with a remote control. This problem is overcome in sublevel 9.2, where the ASVs are able to communicate with additional means of transportation.

Following are the introduction of prototypes at each level:

Level 0 is the lowest achievable autonomy level. PROTEUS [1] is a twin-hull innovative concept, the vessel floats on two articulated inflatables. The command cabin is hanging in between, attached to a dumped structure. The concept has given birth to smaller ASVs like the WAM-V ASV.

Level 1.1 has three remote-controlled vessels, which is regarded as the first step toward an autonomous prototype. In [43] and [72], studies about the hulls, controllers, actuators and dynamic data are accomplished. The Seabax [22, 53] recognizes QR-codes and will be able to respond accordingly. These binary markers can be used for several purposes: they could represent a waypoint, a traffic redirection signal or a building ashore.

Level 1.2 includes a new project sponsored by Rolls Royce [42, 58]. The timeline plans a first deployment of remote controlled ASV with decision making support in 2020.

Level 1.3 is found in the ASV proposed by [19] and Circe from [38]. The controllers onboard are able to store and send time dependent commands to the actuators. The sets of actions are given in an open loop control, which is not autonomous given the limited prediction in a highly disturbed environment.

Level 3.1 refers to the vessels which have path following controllers. ALANIS [11] uses a Line-of-sight guidance technique, combined with a Proportional-Differential (PD) controller. ERON [25] navigate through waypoints with a Proportional-Integral-Differential controller. These prototypes are not able to communicate with remote computers.

Level 3.2 is the level which the largest number of ASVs achieve. Those prototypes have path following controllers and remote connection with computers, but do not have any decision making support system or obstacle detection sys-

Table 5. Autonomy level of ASV prototypes

No.	Prototype	Subsystems				Autonomy	No.	Prototype	Subsystems				Autonomy
		De	Act	Ex	Co				De	Act	Ex	Co	
1	Proteus	1	1	1	1	0	**33**	CRW	2	5	1	4	3.5
2	ASV MUN	1	1	1	2	1.1	**34**	USNA	2	5	2	2	3.6
3	ASV SMU	1	1	1	2	1.1	**35**	IMOCA 60	2	5	2	2	3.6
4	Seabax	1	1	1	2	1.1	**36**	Tito Neri	1	6	1	3	4.2
5	Rolls Royce ASV	3	1	1	1	1.2	**37**	SeaWASP	1	6	1	2	4.4
6	ASV Prototype	1	2	1	1	1.3	**38**	Charlie USV	4	6	1	3	4.5
7	Circe	1	2	1	1	1.3	**39**	Electric boat	5	5	5	2	5.8
8	ALANIS	1	5	1	1	3.1	**40**	Rolls Royce ASV 2	5	6	6	2	5.17
9	ERON	1	5	1	1	3.1	**41**	iNav-1	6	8	1	4	7.3
10	CaRoLIME	1	5	1	1	3.1	**42**	AVALON	6	8	2	2	7.4
11	ENSIETA	1	5	1	2	3.2	**43**	MAINAMI	6	8	2	3	7.5
12	DELFIM	1	5	1	2	3.2	**44**	ROAZ	6	8	2	3	7.5
13	MARV	1	5	1	2	3.2	**45**	ROAZ II	6	8	2	3	7.5
14	WAM-V	1	5	1	2	3.2	**46**	SCOUT	5	5	8	3	8.2
15	SCOAP	1	5	1	2	3.2	**47**	Challenger 2000	5	6	8	2	8.3
16	Zarco	1	5	1	2	3.2	**48**	WUT-1	6	6	8	2	8.3
17	A-TIRMA G2	1	5	1	2	3.2	**49**	ReVOLT	7	8	8	2	9.1
18	A-TIRMA G1	1	5	1	2	3.2	**50**	CS Saucer	8	8	8	2	9.1
19	SailBuoy	1	5	1	2	3.2	**51**	MUNIN	8	8	8	2	9.1
20	OASIS	1	5	1	2	3.2	**52**	ASAROME	8	8	8	2	9.1
21	WaveGlider	1	5	1	2	3.2	**53**	PROPAGATOR 2	8	8	8	3	9.2
22	Lizhbeth	1	5	1	2	3.2	**54**	PROPAGATOR 1	8	8	8	3	9.2
23	Artemis	1	5	1	2	3.2	**55**	Rolls Royce ASV 3	8	8	8	4	9.2
24	ACES	1	5	1	2	3.2	**56**	Delfia-1	8	8	8	5	9.2
25	Swordfish	1	5	1	2	3.2	**57**	Delfia-1 Star	8	8	8	5	9.2
26	ASV	1	5	1	2	3.2							
27	N-Boat	1	5	1	2	3.2							
28	Proto 1	1	5	1	2	3.2							
29	Proto 2	1	5	1	2	3.2							
30	ASV ROBOAT	1	5	1	2	3.2							
31	WAM-V USV16	1	5	1	2	3.2							
32	VAIMOS	1	5	1	2	3.2							

Project 58, 59, 60 cannot be properly classified since key data is missing.

tem. Moreover, the communication is not cooperative, so the vessel only sends real-time data and receives information which is needed for navigation.

Sailing boats are found in this autonomy level. Those boats can control the direction, but they can not manage the speed. The sail position must be adjusted and the boat can not navigate against wind direction. Tracking algorithms are used to reach the designated point. [60], [63] and [40, 59] (N-Boat) have presented solutions. However, they are not able to navigate in complicated paths. The autonomy devices are implemented, but controllers need to be better arranged. A-Tirma version 1 [10] and 2 [26] manage the position of the sails through a fuzzy logic controller.

Sailing boats are especially chosen for the endurance. The power they use is the wind, which is always available at the sea. The energy required to drive controllers and actuators can be taken from a solar panel or a wind turbine. VAIMOS [6] sailed continuously for 19 hours, completing the whole task, which was expecting to achieve complicated maneuvering. During the test, the lack of obstacle avoidance capability brought VAIMOS close to a collision for two times. ASV Roboat [65] navigated for 27 hours in the Baltic sea before a malfunction to the sail trimmer interrupted the mission. The SailBuoy is able to survive up to 6 months only using the batteries. The SailBuoy has a path following controller, which gives the possibility to follow certain streams or animals.

However, the power the sailing bosts use is unpredictable, and the shape makes the vessel limited in the scope. This is why more electric or gasoline fueled vessels are found in level 3.2. The first documented ASV developed is ARTEMIS [57]. Developed in 1996, it was already capable of waypoint navigation through a fuzzy-logic controller of the rudder. The successive ASV, ACES [46], proposed the same functions with a different hull shape. In the following years, many others ASV with same capabilities have been developed: DELFIM [3], Zarco [20], Swordfish [29], Lizbeth [37], the ASV in [56] and WAM-V USV16 [71].

Alternative solutions in terms of fuel have been proposed by OASIS [35] and Waveglider [36]. The first vessel is entirely covered in solar panels, designed to withstand the harsh ocean environment. The Waveglider integrate a solar panel, which powers the sensors and control system, and a submerged unit, which supply the forward motion through fins and wave motion.

Among those ASVs which achieve Level 3.2, MARV [5] is a fully capable research vessel assembled using only off-the-shelf components. This technology is available to everybody, to successfully create ASVs and experiment new controller techniques. In the military scope, the ASVs are being deployed to patrol, following predefined paths, such as the WAM-V [54]. An attempt to avoid collision has been made by SCOAP [18], integrating a passive AIS signal emitter to alert other vessels of the presence of an uncontrolled vessel.

Level 3.5 has a project called CRW [70]. It is a set of identical ASVs, with an original air propeller, which can be deployed in calm waters (canals, lakes). The swarm is able to cooperate by exchange information. The core of the control system is an Android smart phone.

Level 3.6 of autonomy is achieved by integrating a simple obstacle detectors. USNA sailing boat [50] has the simple waypoint navigation system, but uses an ultrasonic range finder to detect obstacles. However, no reaction has yet been implemented. A similar solution is found on board of the IMOCA 60 sailing boat [62]. The vessel are made to navigate non-stop around the world. The sailor on board must take care of his own needs, this is why a robust autopilot is always integrated. Besides, the AIS system is used to communicate and receive information about the presence of other vessels in the close proximity [16].

Level 4.2 includes the ASVs which has the function of dynamic positioning. Tito Neri [23] is a scaled model (1:30) of a real tugboat. It developed to study the dynamic and platooning\leader following behavior of autonomous ships. Now, it is mainly used for educational purposes.

Level 4.4 is the ASV which has a trajectory controller, such as SeaWASP [7, 45]. Her twin-hull is submerged with the use of ballast water to improve the stability. The controller uses a proportional linear controller to correct the heading and velocity and minimize the tracking error.

Level 4.5 involves the function of cooperation. The Charlie USV is a catamaran which is able to cooperate with a leader vessel. The leader sends GPS reading to the ASV which uses her trajectory tracking controllers to follow. The speed is managed to keep a fixed distance respect to the front vessel.

Level 5.8 has the electric vessel developed by Northrop Grumman [64]. The vessel is able to autonomously navigate and react to obstacles. The stereo vision is used to define the side of the river or the acceptable limits in the harbor. Furthermore, the fixed obstacles are discovered with a color blob technique, while the moving one with motion blobs. The vessel is able to navigate without any prior map and detect obstacles with the array of cameras.

Level 5.17 refers to a updated version of ASV planned by Rolls Royce project [58, 42]. By 2030, an autonomous cargo vessel will be presented. She is able to autonomously navigate, but still requiring full time human remote supervision of the actions and decision making.

Level 7.3 is achieved by iNav-1 [74]. iNav-1 has the capability of path following and heading control. A pod propulsion USV heading control system is designed for it based bipolar fuzzy controller. One thing worth to note is that it is able to cooperate with UAVs for synergetic cruises in maritime supervision.

Level 7.4 is achieved by smart sailing boats, AVALON [33] and MAINAMI [52]. AVALON uses weather data and a digital nautical chart to plan routes with a grid-based A* algorithm. The decisions are then passed to the action subsystem, which translates in actual rudder and sail set up, considering the wind direction. However, the obstacles are not considered. In AVALON, a passive AIS system is applied to send information. MAINAMI communicate with underwater vehicles by means of an acoustic device.

Level 7.5 includes the ROAZ and the follow up ROAZ II [49]. These vessel navigates with a GPS waypoint controller. The surrounding are explored by two cameras, which are able to process the images and define the target position. Once the target is locked, the vessel follows the object at a fixed distance [48].

Level 8.2 includes the project SCOUT, a set of kayaks [21]. The goal is to monitor wide shallow areas and cooperate toward this achievement. The common protocol used to communicate with the remote location gives the ability to these vessels to avoid collisions with each other. This is not a robust approach as of now, since exchange of data between vessels is limited. In the future, if rules change and make mandatory the use of AIS, the simple exchange of information between vessels could avoid the collision.

Level 8.3 is achieved by SEADOO Challenger 2000 [41] and WUT-1 [17, 44]. Cameras, ARPA radar and AIS, together with detailed nautical charts, give the vessel the ability to compute long term path. WUT-1 is able to automatically plan routes according to the navigation objectives and track the preplanned routes. Moreover, WUT-1 can sense the obstacles and determine an anti-collision route with A* algorithm and Artificial Potential Field.

Level 9.1 is a quiet high level. Almost all the vessels which have reached this level are limited to a remote connection, without considering the cooperative communication with other vessels. It is interesting to notice that all the projects or prototypes in this level have been published in recent two years.

The sailing boat ASAROME [55] uses a PD controller for tracking. A 360 camera is applied to detect obstacles. This data is combined with the reading from the underwater sonar and the inertial measurement unit to create a 3D map for a potential-based reactive path-planning.

The CS Saucer is a small circular autonomous vessel [39]. It is equipped with a 2D Lidar to explore and maneuver in unknown terrains. Based on the map made by Lidar, the decision making system can find the path to follow. One drawback of this highly autonomous experiment is the limited usage in agitated sea waters. The prototype has only been tested inside a water basin. For this reason, the vessel is not equipped with a GPS, but relies on IMU for moving.

ReVolt cargo vessel [67, 8] and MUNIN [51] focus on the autonomous vessel which can be aware of the situation around it, and navigate with an occasional supervision. In both cases, the remote control is chosen as a fallback option. Both ReVolt and MUNIN are now ship concepts. For the purpose of testing, the autonomous capabilities of ReVolt, a 1:20 scaled model has been built.

Level 9.2 is achieved by some on-going projects. PropaGator [31, 30, 34] has managed to achieve a really high level of autonomy, by using Lidars, camera vision and cooperation with other autonomous vehicles. PropaGator is able to recognize and avoid obstacles, recognize signs, and communicate with a quad-copter to deploy it and recover it once completed the mission. The only lacking is long term route planning. As of now, the planning is limited to the area explored by the cameras and LiDAR.

Delfia-1 [66] and the follow up Delfia-1 Star [53] , also reach Level 9.2. Their shape is designed to make maneuvering applications in crowded environments easier than actual solutions allowing at the same time the possibility to combine multiple Delfia ships in one bigger platform. They have already pass the test of path following, collision avoidance and dynamic positioning. Moreover, they are capable to communicate and cooperate with not only vessels, but also other agents, such as infrastructure operators. The ASVs have a remote controlled option.

Rolls Royce is aiming to achieve the same level by 2035 with a cargo vessel [58, 42]. Their goal is to have an autonomous ocean going vessel, which are able to make decision, take actions and handle exceptions autonomously. The cooperation can be extended to ports and other vessels in the fleet, in order to optimize the overall operations.

4 Trends in ASV research

The information summarized in the previous sections have been combined in order to understand the status and future trends of ASVs in this section. As the development time of those USV usually lasts more than 3 years, in this section, we use 3 years as the class interval.

The first focus is on the number of prototypes developed. Fig. 1 shows a large increase on the number of ASV projects.

As analysis in former section, the autonomy level that most ASVs reached is Level 3 (Figure 2). However, many on-going projects are aiming at high level autonomy vessels which are able to make decision, take actions and handle exceptions autonomously. So far, no ASVs have achieved Level 10 automation.

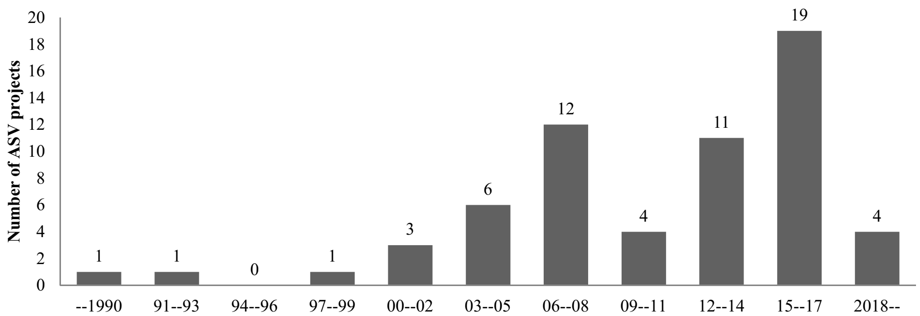

Fig. 1. The number of ASVs developed

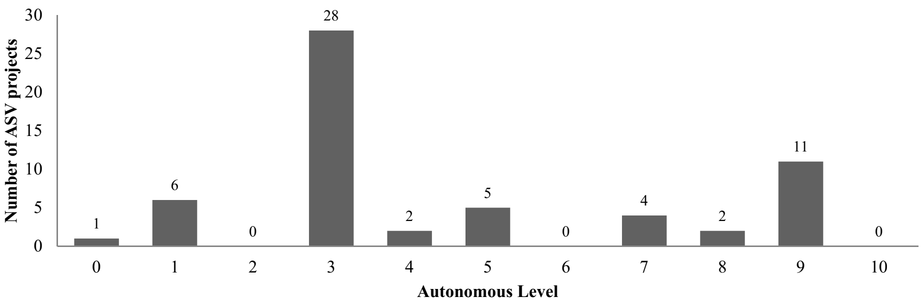

Fig. 2. The number of ASVs in each Autonomy Level

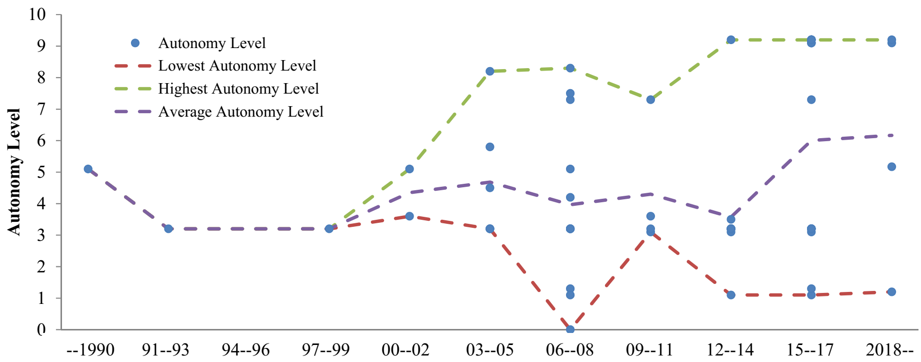

Fig. 3. Trend in the automation of vessels in the past years

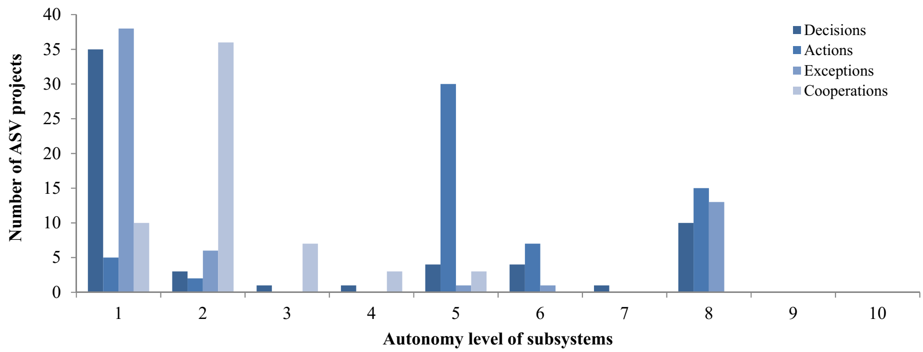

Fig. 4. Trend in the automation of vessels in the past years

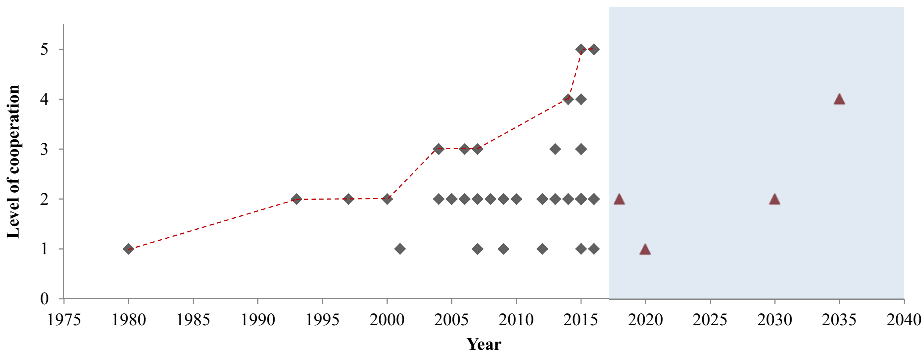

Fig. 5. Cooperation level reached through the years

The automation of the vessels has been increasing through the years. In Figure 3, the range of autonomy levels that the projects achieve become larger because the number increase. The highest level of autonomy that ASVs can achieve increase year by year. The realization of vessels with lower autonomy levels are the basis to develop autonomous vessels with higher autonomy levels. Moreover, vessels with different level of autonomy have different applications.

Looking into the autonomy level of subsystems (Figure 4), the highest autonomy level that the decision making, action taking and exception handling is 8. Thanks to the development of searching algorithms and autopilot, many vessels achieve high autonomy level of the decision making and action taking subsystem. The action taking systems owns the highest level of autonomy with an average 5.4. Then, the decision making system has an average 3.0. The autonomy for the exception handling system are relatively low. Many prototypes with high overall autonomy levels still needs human assistances. For the newly introduced cooperative subsystem, some research groups have already realized the importance. Because the concept of cooperation between agents is a new field to explore, only a limited number of vessels is above Level 2 is found. However, we can still find a rising trend in Figure 5.

From the perspective of dimensions, most of existing ASVs prototypes are scaled models whose length are less than 10 m. Some models are serve as test bench in researching sensor fusion, collision avoidance and other relative software for the full scale autonomous vessels. Moreover, some small dimension prototypes are used for scientific purposes, such as maritime monitoring and oceanographic observation.

5 Conclusions and further research

ASVs have been developed for more than 20 years. In the latest years, it seems that the technology has reached a point where the usage of those vessel could become more extended and integrated in the current environment. Small and big stakeholders are investing on the development of increasingly big autonomous ships. In the literature, many ASV projects have been successfully realized, and as many are still under development. Just a few ASV have reached mass production, since only a niche market is using those devices. In the literature there is a lack on research about different applications and suitable environments for the deployment of ASV.

In this paper, we provide an overview of the existing projects considering their main components, dimensions, scope and deployment year. The automation level that each prototypes achieved are elaborated according to an innovative categorization proposed in our previous work [61]. The analysis about existing research helps to gain knowledge about the emerging concepts and techniques that have been applied in ASV research.

Further comparisons between the existing projects has lead to the agreement that the research on ASVs is rapidly increasing. The autonomy level is following the same trend, proposing new intelligent solutions. The scope of the newly designed autonomous vessels is shifting from small ASVs for scientific researches to bigger cargo crafts. The research of cooperation in ASVs is still at beginning but shows great potential.

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