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A review on improving the autonomy of unmanned surface vehicles through intelligent collision avoidance manoeuvres

S. Campbell [1], W. Naeem *, G.W. Irwin

Energy, Power and Intelligent Control, School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast BT9 5AH, UK

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ABSTRACT

In recent years unmanned vehicles have grown in popularity, with an ever increasing number of applications in industry, the military and research within air, ground and marine domains. In particular, the challenges posed by unmanned marine vehicles in order to increase the level of autonomy include automatic obstacle avoidance and conformance with the *Rules of the Road* when navigating in the presence of other maritime traffic. The *USV Master Plan* which has been established for the US Navy outlines a list of objectives for improving autonomy in order to increase mission diversity and reduce the amount of supervisory intervention. This paper addresses the specific development needs based on notable research carried out to date, primarily with regard to navigation, guidance, control and motion planning. The integration of the International Regulations for Avoiding Collisions at Sea within the obstacle avoidance protocols seeks to prevent maritime accidents attributed to human error. The addition of these critical safety measures may be key to a future growth in demand for USVs, as they serve to pave the way for establishing legal policies for unmanned vessels.

1. Introduction

Following decades of research and development focused on the autonomy of aerial and underwater vehicles, comes resurging interest in Autonomous Surface Vehicles (ASVs). This is timely with the Defence Advanced Research Projects Agency's (DARPA's) announcement that it requires $3 billion in fiscal 2012 for projects involving ASV development for submarine tracking (Doyle, 2011). Extensive research has been carried out to date on Unmanned Underwater Vehicles (UUVs) due to implications for oil and gas exploration, deep sea pipeline monitoring and mine detection. Furthermore, research in Unmanned Aerial Vehicles (UAVs) has also largely overshadowed that of Unmanned Surface Vehicles (USVs) as they have become a superior tool in military strategies, e.g. the deployment of *Predator* and *Reaper* drones in Iraq and Afghanistan by the United States Air Force. UAVs are now heavily relied upon for surveillance, intelligence, search and rescue, reconnaissance and strike missions. Significant attention has also been given to Unmanned Ground Vehicles (UGVs) which encompass driverless cars, military tools for surveillance or bomb disposal and mechanical mule type vehicles for transporting heavy payloads. *BigDog*, for instance, is a well-known quadruped robot designed by Boston Dynamics to carry over 150 kg payload in difficult terrain and has since been adapted for autonomous navigation (Wooden et al., 2010). Technical similarities can be drawn between UGVs and USVs particularly in terms of the number of degrees of freedom and the need to safely operate in the presence of ambient traffic. However, motion control of underactuated ships in the presence of harsh environmental disturbances and an open navigational space poses far greater challenges.

It should be noted that semi-autonomy is highly typical of unmanned vehicles and in the past has often been favoured over full autonomy due to the diverse nature of missions. Further development of these uninhabited systems is required to extend their capabilities to include more complex and optimal mission planning in order to become less reliant on human interactions and subject to human error. The latest developments in the fields of artificial intelligence, advanced smart sensors, wireless networks and optimisation techniques now present greater opportunities than ever before for USVs and maritime technology on the whole (Corfield and Young, 2006).

The aim of this paper is to review and highlight the design aspects of the USV Navigation, Guidance and Control (NGC) system with respect to the International Regulations for Avoiding Collisions at Sea (COLREGs). The COLREGs describe potential collision scenarios such as crossing, head-on and overtaking, to mention a few (Commandant, 1999) and suggests possible manoeuvres to avoid a collision. Although the rules provide a set of guidelines for safe manoeuvring at sea, they were written for human

* Corresponding author.
E-mail addresses: scampbell49@qub.ac.uk (S. Campbell), w.naeem@qub.ac.uk (W. Naeem), g.irwin@ee.qub.ac.uk (G.W. Irwin).
[1] Principal corresponding author.

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navigators, who, based on their experience alter the course of the ship accordingly. This subjective nature of COLREGs is one of the major causes of ship collisions. It is estimated that human error contributes to between 89% and 96% of marine collisions, both active and latent, e.g. amateur manoeuvring (Rothblum, 2000). The *RMS Titanic* which infamously sank due to collision with an iceberg (Brown, 2000) as well as the *Exxon Valdez* oil spill disaster which struck a reef (Leacock, 2005) and the *MV Doña Paz* ferry disaster upon colliding with the *MT Vector* (Strauch, 2004) are amongst the most devastating peacetime maritime catastrophes of all time. Each of these collisions has been attributed to some form of human error, which could have been prevented. Poor judgement and failure to respond promptly are issues which can be resolved with an intelligent Obstacle Detection and Avoidance (ODA) system, substantially minimising risk.

The modern COLREGs were set out in 1972 by the International Maritime Organisation (IMO) as a set of guidelines for vessel encounters at sea, i.e. Rules of the Road. It is expected that all vessel operators comply with these regulations, which outline procedures for determining right of way and correct avoidance manoeuvres. Thus, if marine vessels can operate intelligently in accordance with these guidelines, many traffic-related accidents at sea caused by human error could be avoided. It should be stressed that motion planning for marine vehicles has been investigated in detail, however little attention is paid to COLREGs compliance. This lack of interest can be attributed to a number of factors. The foremost is the non-existence of any laws or regulations for the operation of USVs. Hence, until now the industry has not demanded USV development in preference to manned vehicles, primarily due to deficiencies in the decision-making abilities of an autonomous system.

In the last few years, noteworthy reviews have been carried out outlining USV motion planning and obstacle avoidance methodologies. One such paper (Statheros et al., 2008) describes various soft computing techniques for obstacle avoidance, mentioning only limited heuristic search methods. It does not address the USV control systems or COLREGs themselves and how to implement them in any detail. A recent review of close-range collision avoidance (Tam et al., 2009) gives a chronological account of approaches taken to the guidance problem and discusses related studies which tackle path planning with regard to collision avoidance. The authors did not discuss unmanned vehicles, but rather focussed on increasing the autonomy of manned craft to avoid human error during navigation when executing COLREGs. Another paper (Benjamin et al., 2006) describing behaviour-based control using Interval Programming discusses COLREGs protocol selection and action averaging accompanied by sea trials. However, only the four main COLREGs manoeuvre-based rules are investigated and the vessels used in the trials maintain wireless communication in order to determine the position of the other without relying on sensor information. It is concluded therefore, that existing literature has not sufficiently addressed problems establishing behavioural patterns based on obstacle classification (i.e. static, dynamic, geographic or other vessels) and complex encounter situations regarding COLREGs. It is also necessary to develop fail-safe methods for reactive avoidance, should the USV encounter unforeseen situations. This paper presents the recent developments in a wide range of fundamental topics relating to USVs and how the synthesis of these developments along with robust real-time motion planning can provide a comprehensive solution for a COLREGs compliant USV.

The following sections discuss the present state of USV development and highlight deficiencies and issues yet to be satisfactorily addressed. Through consideration of existing USV prototypes, NGC aspects and advanced motion planning techniques for the assimilation of COLREGs, this literature identifies key avenues to be explored for the accomplishment of an intelligent, autonomous USV.

2. USV prototypes and subsystems

2.1. Research vessel prototypes

The majority of USV research prototypes have been designed and developed for the purposes of collecting oceanographic data, i.e. bathymetry, pollution monitoring, etc. European prototypes include the *Measuring Dolphin (MESSIN)*, developed by the University of Rostock, Germany (Majohr et al., 2000) and the autonomous catamaran, *Charlie*, from The Institute of Intelligent Systems for Automation, Genova, Italy. *Charlie* is a catamaran shaped prototype vessel which has been used to gather sea surface samples during the *XIX* Italian expedition to Antarctica (Bibuli et al., 2008). In the UK, notable contributions in the field of USVs have originated from the Marine & Industrial Dynamic Analysis Research Group (MIDAS) at the University of Plymouth in the development of the *Springer USV*, shown in Fig. 1a. The *Springer* has been developed for conducting environmental and hydrographic surveys in coastal waters (Naeem et al., 2006).

The key to the future development of USVs heavily depends on advances in the underpinning technology which determines their capabilities. One popular development goal involves collaboration with one or more UUVs to create a relay network with wireless communication. The *DELFIM* developers from Dynamical Systems & Ocean Robotics (DSOR) at Instituto Superior Técnico (IST), Lisbon have also made many significant contributions to the field and have since created the *DELFIMX* in 2004 (a successor ASV for increased autonomy and improved hydrodynamics) and the Caravela (a long-range vessel). The *DELFIM*, appearing in Fig. 1b was originally developed for automatic marine data acquisition, acting as an acoustic relay between a UUV and support vessel (Alves et al., 2006). In the USA, the Massachusetts Institute of Technology (MIT) have developed a family of USVs which include a $\frac{1}{7}$ scale fishing trawler type vessel, ARTEMIS (1993), the catamaran models, *ACES* (1997) and *AutoCat* (1999), and the *SCOUT* vessels (2004). Of all these prototypes, the kayak type, *SCOUT* vessels have successfully implemented COLREGs at a basic level for head-on situations whilst maintaining wireless communication (Benjamin and Curcio, 2004). A USV platform adapted from a *SEADOO Challenger 2000*, originating from the Space and Naval Warfare Systems Center (SSC) San Diego has also executed obstacle avoidance in accordance with the Rules of the Road during trials and is discussed in a later section (Larson et al., 2006).

2.2. Military vessels and USV strategies

USVs were in use as early as World War II, where remotely controlled vessels were deployed as gunnery and missile target systems (Corfield and Young, 2006). Since the 1970s the concept has been largely revisited as Mine Countermeasure Systems (MCMs) in the form of multiple drones in communication with a mother ship (Saunders, 2004). A surface, underwater and aerial drone network in communication represents a potentially powerful tool in military surveillance, which would require seamless operation and data transfer.

QinetiQ Ltd., produced a semi-autonomous USV using Shallow Water Influence Minesweep System (SWIMS) technology in 2003 (Corfield and Young, 2006). The *Israeli Protector (Rafael Advanced Defense Systems)* (PROTECTOR, 2010), shown in Fig. 1c is an operational weapon-loaded USV deployed for maritime security and defence in the Persian Gulf. Similar to the *US Spartan* USV (owned by the Naval Undersea Warfare Center) (Bertram, 2008), a wide

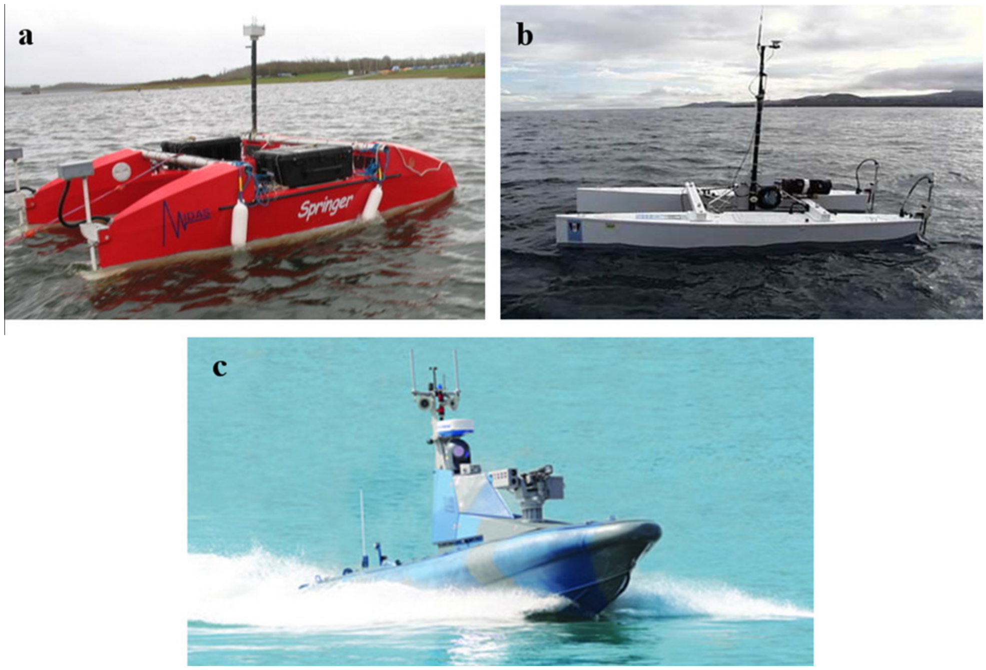

Fig. 1. USV Prototypes; (a) *Springer* (Marine and Industrial Dynamic Analysis Research Group, 2007), (b) *DELFIM* (Alves et al., 2006), and (c) *Israeli Protector* (PROTECTOR, 2010).

variety of plug and play missions are easily integrated including anti-terror, surveillance and electronic warfare. It is capable of speeds of up to 20 m/s and is considered one of the greatest USV achievements to date in terms of autonomy, however it still relies significantly upon operator guidance and remote control (PROTECTOR, 2010).

In July 2007, the Program Executive Officer for Littoral and Mine Warfare chartered the *USV Master Plan* for the US Navy. This outlines the USV development needs for the goals of the Department of Defense (DoD) approaching 2020. The plan was published to academia, industry and research institutions in order to direct their efforts towards governmental needs (United States Navy, 2007). Those needs which have been identified involve increasing the level of autonomy to reduce data inflow and outflow to and from the operator, and investigating the necessary rules for maritime law for the operation of autonomous (armed) vehicles which should be integrated within the system design. Other areas which are to be addressed include automatic target recognition, obstacle and collision avoidance and launch and recovery.

The primary need with regard to the NGC system is increased autonomy in terms of obstacle recognition and appropriate avoidance manoeuvres to minimise the dependency on operator intervention. Vision systems should, at a basic level, detect objects in advance and categorise them as static or dynamic and if applicable, predict their future velocity and position in order to determine an appropriate course of action. More advanced vision systems may be capable of object classification, i.e. class of vessel or building a map of an unknown environment in real-time. Avoidance manoeuvres include diverting around static geographical features such as islands or shallow waters, evading dynamic hostile targets or simply avoiding collision with other approaching vessels in compliance with COLREGs. The manpower required during ship docking could also be significantly reduced by an automatic docking and launch system. In the following section, an overview is given of the individual hardware components, and several variations based on these existing prototypes.

2.3. USV subsystems

The block diagram in Fig. 2 indicates the main components and sub-systems on-board a USV, according to existing prototypes. Presently several variations of the craft's hull type exist, each suited to their respective purposes. The catamaran and kayak types are highly popular in research due to their ease of mounting and loading. Whilst kayak-type hulls such as *SCOUT* are convenient to manufacture, twin-hull types similar to the *Springer* are often preferred as they offer increased roll stability. Rigid Hull Inflatable Boats (RIBs) perform well in endurance missions and hence are well suited to military applications primarily because of their capability to carry large fuel tanks and payloads (Caccia, 2006). Most of the named prototypes exhibit a rudder-propeller system for propulsion and heading control, i.e. steering. The *DELFIM* uses an alternative method based on differential thrust, which engages two independent motors attached to each hull yielding a thrust vector. Problems associated with the cost and inconvenience of refuelling has generated interest in investigating substitute methods of powering the USVs as an alternative to electricity or gasoline. The *Wave Glider* by Liquid Robotics is a commercially available USV which converts wave motion into thrust and utilises solar-powered sensors. This renewable technology is very favourable for future marine craft designs, particularly where endurance is of paramount importance (Wave glider concept, 2010).

NGC modules generally consist of commercial off-the-shelf (COTS) sensors coupled with on-board computers which carry out the path planning and generate signals to directly control the actuators. With this in mind, virtually any marine surface craft can be converted into a USV for a sufficient, cost-effective platform. SSC, San Diego adapted the jet-powered *SEADOO Challenger 2000* to obtain a USV platform for collision avoidance testing using many basic components from existing UGV platforms (Larson et al., 2006). On-board GPS (Global Positioning System) or Differential GPS (DGPS) is necessary to determine the position of the USV, along with a basic inertial navigation system. DGPS is a more expensive, enhanced version of GPS which uses known reference

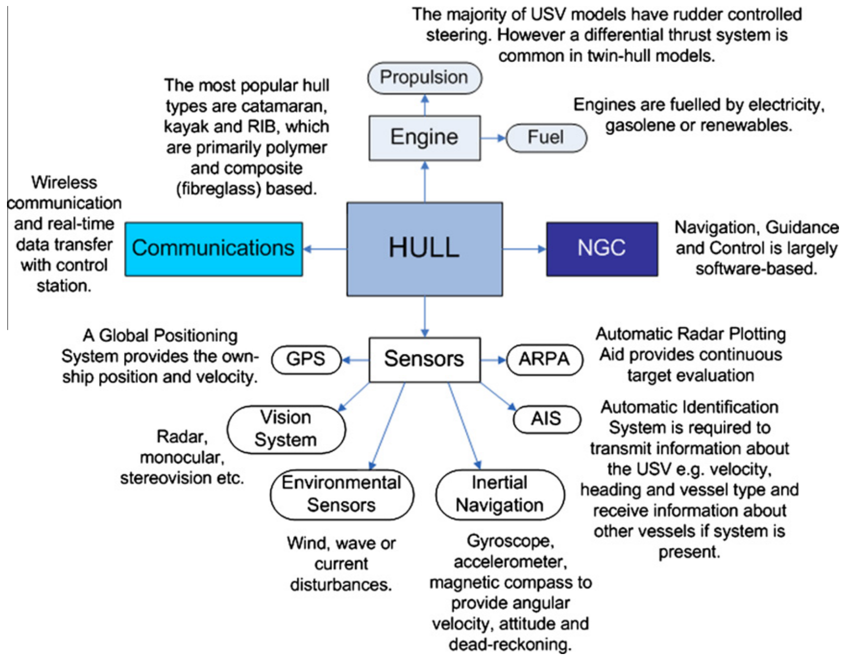

Fig. 2. USV Hardware and Sub-systems.

stations to apply a correction factor and give positional accuracy within 1–10 m.

Typically the vision system is comprised of radar sensors with an Automatic Radar Plotting Aid (ARPA) for obstacle, vessel, landmark or coastline detection. This system is capable of measuring the proximity of an object and its relative velocity to the observer. Ideally the vision system should positively identify the class of object (with the aid of an Automatic Identification System (AIS)) and react accordingly, e.g. perform COLREGs manoeuvres for approaching ships. It is compulsory by law for vessels to be equipped with an AIS as of December 2004 (International convention for the Safety of Life at Sea (SOLAS), 1974/1980) if they meet the criteria of passenger ships, over 500 gross tonnage, or over 300 gross tonnage and engaged on an international voyage. They should transmit information about the vessel's identity, velocity and course and automatically receive the same information from other AIS-equipped vessels. This greatly aids the identification process of other marine traffic in advance, so sensory information becomes redundant in this case. Radar limitations such as skewed data due to fast turning manoeuvres, false alarms and lack of detection of smaller ships or emerging vessels have lead to specialised research in monocular and stereo vision for this type of application (Larson et al., 2006).

Without doubt, the most common guidance law is Line-Of-Sight (LOS), which was used in some of the first guided missiles developed in the 1940s (Berglund, 2000). Using a database of waypoints, a trajectory is generated in the form of a straight line to the next destination. Alternative guidance laws include vision-based, chemical-based (biomimicry), Lyapunov-based and potential field theory. However, without the integration of an Obstacle Detection and Avoidance (ODA) subsystem, the vessel will collide with any objects present along the generated path.

An ODA module enhances the autopilot systems within existing USV designs which rely on supervisor interaction to avoid approaching objects by carrying out manual waypoint replanning. This is not the most efficient method for avoidance and is subject to operator error. The primary requirement of the controller, or autopilot is to ensure the underactuated vessel follows the generated trajectories as accurately as possible by controlling the actuators directly. It may be necessary to track the time-parameterised path or simply regulate the heading angle using basic PID control (Roberts, 2008), with the former requiring more advanced optimal or adaptive control techniques, such as $H\infty$ (Lefeber et al., 2003) or Linear Quadratic Gaussian (LQG) methods (Naeem, Sutton, and Chudley, 2007). State estimators are often required in order to compensate for disturbances present, such as waves because as with virtually all real systems, all of the states are not known. Intelligent control methods have been adopted with some success as in Yang and Zhao (2006) and Zhou et al. (2010) which have used Artificial Neural Networks (ANNs) and fuzzy techniques respectively. Guidance and control are discussed in greater detail in Sections 3 and 4.

The next section presents the control subsystem design of USVs. Autopilots play a crucial role in ensuring the vehicle adheres to the path generated by the (COLREGs-compliant) guidance subsystem. The most suitable controller type depends largely on the motion planning objectives, which are discussed in Section 4. General control techniques will now be considered for a range of common objectives.

3. USV control

The marine research community are continually developing and applying state-of-the-art control methods to autonomous vehicles, implementing modern control techniques for enhanced performance. The control selection process for a USV depends upon the dynamic model (vessel type), e.g. underactuated, high speed, rudder or thruster controlled, etc. and the vessel mission. The range of controllers include;

- Surge velocity control.
- Heading control.
- Traditional autopilot (yaw and sway control).
- Turning manoeuvre control.
- Positional control.
- Course keeping (time-parameterised trajectory tracking).
- Roll stabilisation.
- Cooperative behaviour with other vessels.

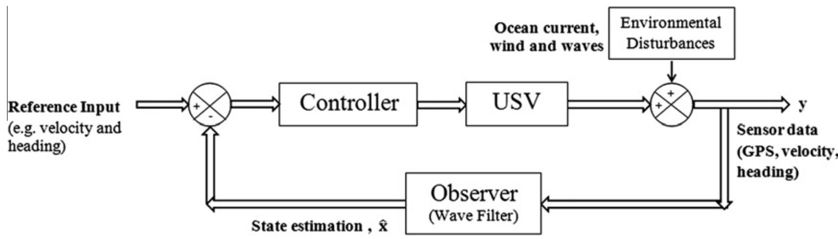

Fig. 3. Generic controller structure for USV.

and combinations of the above. Control objectives can involve one of setpoint regulation, path following, trajectory tracking or manoeuvring. Autonomous vessels with obstacle avoidance are likely to require course keeping and manoeuvring control to avoid collisions, as position with respect to time is critical, particularly in the presence of dynamic obstacles. Cooperative behaviour between vessels of same and different types, e.g. formation control, mother and drone ships or vessels in communication with aerial or underwater vehicles is a topic which has received much attention in recent years, however it is considered to be outside the scope of this review.

3.1. Controller types

The first recognised automatic steering system is accredited to Elmer Sperry who patented the gyrocompass in 1911. The system, nicknamed 'Metal Mike' was quickly adopted and implemented successfully by the US Navy during World War I. Nicholas Minorsky, who was renowned for his work in nonlinear mechanics, subsequently published theory for a three term or PID (Proportional-Integral-Derivative) controller for "an efficient helmsman" which "keeps the ship accurately on her course by exerting a properly timed meeting and easing action on the rudder" (Minorsky, 1922).

Despite the noted success of the marine research community in the implementation of many advanced and intelligent control schemes, the industry standard still largely favours classical PID approaches, particularly for autopilot design. However there have been more recent extensions of PID theory for nonlinear control applications (Fossen, 2000). PID is often sufficient for the SISO (Single-Input-Single-Output) case, e.g. where the rudder angle or differential thrust vector is manipulated to produce a reference heading output. One of the most problematic disturbances are ocean waves, which can cause severe actuator damage due to the oscillatory signal feedback and so it is often avoided by including a low pass filter or introducing a deadzone. Successful attempts have been made to control velocity and yaw simultaneously by multi-loop or cascade PID control (Lefeber et al., 2003). Adaptive techniques have been applied to PID control in the presence of various environmental conditions and for a range of vessel speeds, namely fuzzy adaptive control, which mimics the behaviour of a human helmsman. Challenges with a fuzzy approach include defining suitable membership functions, de-fuzzification laws and optimal criteria (Nguyen et al., 2003).

Optimal control techniques such as $H\infty$ and Linear quadratic optimal techniques have been used extensively for multivariable regulation control, i.e. yaw and velocity. Because an LQR controller (Linear Quadratic Regulator) assumes that all states are known or measurable, which is not realistic, LQG (Linear Quadratic Gaussian) methods are generally favoured, with a Kalman Filter in cascade for estimating the unknown states via real-time integration.

Unlike LQR, LQG does not necessarily guarantee robustness and hence requires closed loop stability analysis. LTR (Loop Transfer Recovery) can overcome this problem, regaining some robustness by adding noise to the system input for pole/zero cancellation (Naeem, Sutton, and Ahmad, 2003). Fig. 3 shows the control architecture for the general case, where the observer block in the feedback loop could be a Kalman estimator or a simple low pass filter.

3.2. Trajectory tracking

An example of a basic trajectory which a vessel may be required to track is Cartesian position with respect to time.

$$\Phi(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \tag{1}$$

For this particular scenario, it is necessary to directly control the surge speed and yaw defined by a time-parameterised reference. The author in Fossen (2011) describes the procedure for modifying the LQR design via reference feedforward for the tracking problem. The tracking error is minimised by introducing integral action, where z is the integral state.

$$\dot{z} = y = Cx \tag{2}$$

An adaptive fuzzy autopilot such as that in Velagic et al. (2003) negates the need for a mathematical model and accounts for nonlinearities by neglecting ship dynamics. Other intelligent approaches based on Artificial Neural Networks (ANNs) and Neurofuzzy methods are summarised in Roberts et al. (2003). Neural Networks are capable of representing the nonlinear ship dynamics and hence through learning, allow the system to perform satisfactorily in a wide range of scenarios and environments. Limitations with adaptive linear control methods include instability outside of the predetermined operating conditions and nonlinearities and discontinuities during manoeuvring for underactuated vessels. Nonlinear methods such as the iterative Lyapunov-based technique proposed by Aguiar et al. (2003) can potentially overcome these issues, maintaining global stability whilst tracking a smooth, time-parameterised trajectory and thus have retained active interest within the research community to the present day.

4. USV guidance and motion planning

Having established the pre-requisites, attention is now focussed on the review of existing USV guidance and motion planning methodologies with a view to modifying them for COLREGs implementation. *Guidance* implies directing the motion of the USV along the predetermined course by providing necessary controller inputs, i.e. velocity and course reference data. *Motion planning* describes the actions to be executed via discrete stages and manoeuvres which account for the vehicle's dynamics and is a more general term. Here, some of the most common techniques contributing to the USV motion planning task are presented, from environment representation to path following.

4.1. Motion planning objectives

Fundamental guidance laws generally assume an obstacle-free path. Motion planning implies that obstacle avoidance may be an integral part of the process. The motion objectives can be split into four main categories as outlined by Fossen (2011) and Breivik and Fossen (2008);

- **Setpoint regulation**: Assumes the heading angle is constant, without temporal considerations.
- **Path following**: Refers to following a desired, non-time parameterised path.
- **Trajectory tracking**: The output state must be driven to a desired trajectory, adhering to both predefined temporal and spatial constraints. Only the current information about the target motion, if any, is known.
- **Manoeuvring**: Relates vehicle motion to feasible path following, often with less importance placed on time in favour of spatial constraints.

The objective selection depends on the ODA scenario, with setpoint regulation being the most trivial case. If incorporating COLREGs, setpoint regulation and path following without temporal consideration will not be sufficient, as velocity is critical whilst executing manoeuvres.

4.2. Obstacle detection and avoidance behavioural architecture

The ODA requirements must be clearly defined before attempting to construct a feasible solution, for example, the vehicle may be designed to navigate in a mapped environment with known, static obstacles. This case requires only global path planning, coined as 'deliberative path planning' which can be conducted offline via optimisation theory such as linear programming, or common path finding heuristic algorithms such as A*. The multi-objective optimisation problem, considering dynamic constraints or multiple simultaneously encountered objects, has led to proposed solutions using Fuzzy Logic Decision Making processes (Perera et al., 2010) or a fuzzy-neural interface (Liu and Shi, 2005), adopting human-like behaviour and learning to quantify qualitative collision avoidance criteria. An increasingly popular approach to this type of optimisation problem is the use of Evolutionary Algorithms such as Genetic Algorithms (GAs) (Hong Qu et al., 2005) or Ant Colony Optimisation (ACO) (Zeng et al., 2009), etc. When the environment is unknown or only partially known and obstacles are dynamic, the problem is described as NP Hard (Non-deterministic Polynomial), therefore an optimum solution will not be guaranteed, but all constraints can be satisfied if a solution exists (Sait and Youssef, 1999).

Due to computational requirements and time constraints, it is desirable to carry out the majority of path planning tasks offline before the mission commences. Any subsequent replanning due to changing circumstances will then be carried out online as required. This forms the basic hierarchical structure of a modern NGC architecture as outlined in Fig. 4 inspired by works from Tan (2006), Wu et al. (2009) and Casalino et al. (2009).

The general form of an ODA system ideally consists of a combination of reflexive and deliberative avoidance modules, i.e. a hybrid structure. The autonomous vessel will follow a predetermined path generated offline finishing at the global target, based on known data about the environment. This should incorporate avoidance techniques for stationary obstacles such as islands, shallow waters, buoys, etc. It is possible that no information is known about the environment prior to the mission, other than the destination coordinate. As the vessel encounters obstacles within its sensor range, it is required to carry out standard avoidance techniques or evasion patterns depending on the object classification, e.g. tanker ship moving due East at approximately 20 knots at a distance of 140 m at coordinates, x, y. With a deliberative (high level) ODA only, a sense-plan-act approach is taken. A map of the current environment is maintained and the system uses reasoning to make behavioural decisions, which can be optimised as far as possible before being executed in sequence (Jong Tamba et al., 2007). However changing environments are known to cause unpredictable or unresponsive behaviour (Tan, 2006). Collision with a dynamic obstacle is also possible, as the computationally-intensive algorithms are not designed to run in real-time.

The reflexive ODA module alone acts as a very low level, sense-react approach, which is not usually capable of performing high complexity manoeuvres (Jong Tamba et al., 2007). As a standalone system, it does not contain any information about the environment or mission, i.e. the global path. It is responsible only for local path re-planning and hence could easily cause the vessel to become trapped, e.g. in a dead end. A desired solution is therefore to integrate the two types of modules into a deliberative-reflexive hybrid architecture to handle both the global path and local re-planning scenarios. However, inadequate synthesis and coordination between modules or layers could potentially lead to very erratic behaviour exacerbated by mixed signals and random discrete switching.

4.3. Map representation

Accurate environmental mapping is essential to the path planning process. The vessel's environment or Composition Space (CSpace) can be represented in a number of ways, broadly qualitatively or quantitatively.

- *Qualitative or topological mapping* represents features without reference to numerical data and is therefore not geometrically exact. It consists of nodes and arcs, with vertices representing features or landmarks.
- *Quantitative mapping*, otherwise referred to as metric mapping adopts a data structure which is feasible for path planning based on waypoints, or sub-goals. Optimisation algorithms will attempt to find the optimum route.

Examples of popular metric or grid-based techniques are depicted in Fig. 5 and are briefly outlined below (Mooney, 2009):

- **Meadow Maps**: Convex polygon representation with edges connecting intersecting features e.g. vertices. Waypoints are nodes connecting these edges. The vessel can be represented as a point in space due to the presence of boundaries.
- **Voronoi Diagrams**: Space is decomposed into convex polygons or triangles (Delaunay Triangulation) encasing nodes which are equidistant to all edges. The resulting path connects the Voronoi vertices.
- **Regular Occupancy Grid**: This is the most basic form of graph representation, whereby the CSpace is decomposed into rectangular cells. The entire cell is considered to be occupied if any point in the cell is occupied by an object. High density grids are more accurate but require additional memory.
- **Quadtree Mapping**: The CSpace is recursively subdivided into four, i.e. a form of Recursive Dimensional Clustering. The varied nature of the resolution is an efficient method of memory storage.

For global path planning, a map of the known environment will form the basis of the CSpace. Any further mapping information can be obtained by local region discretisation from sensor data. Nodes are grouped where appropriate to conserve memory, as in most SLAM (Simultaneous Localisation and Mapping) techniques, which usually achieve sparse spatial decomposition. Path smoothing algorithms are applied upon constructing a path to eradicate jerky motion which can have adverse effects on the lifespan of the actuators.

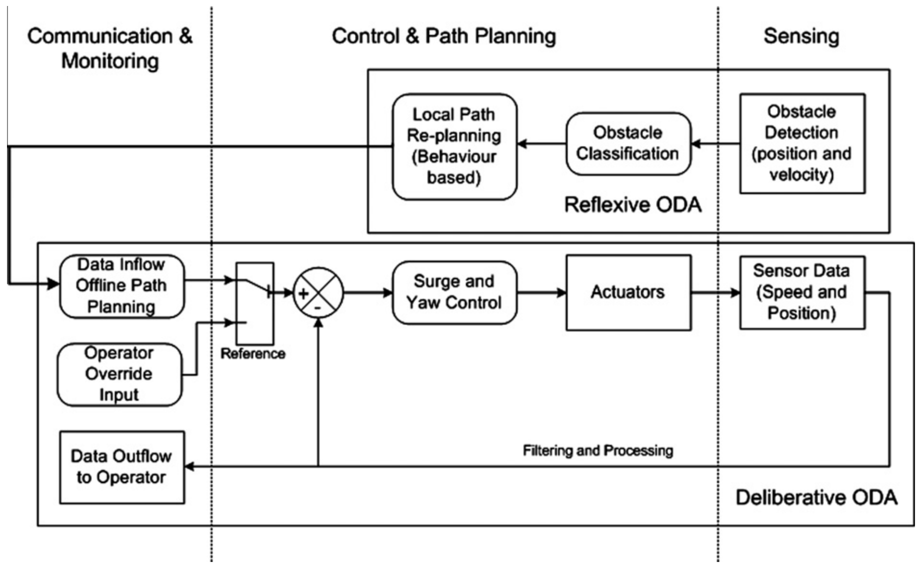

Fig. 4. General form of architecture based on the literature.

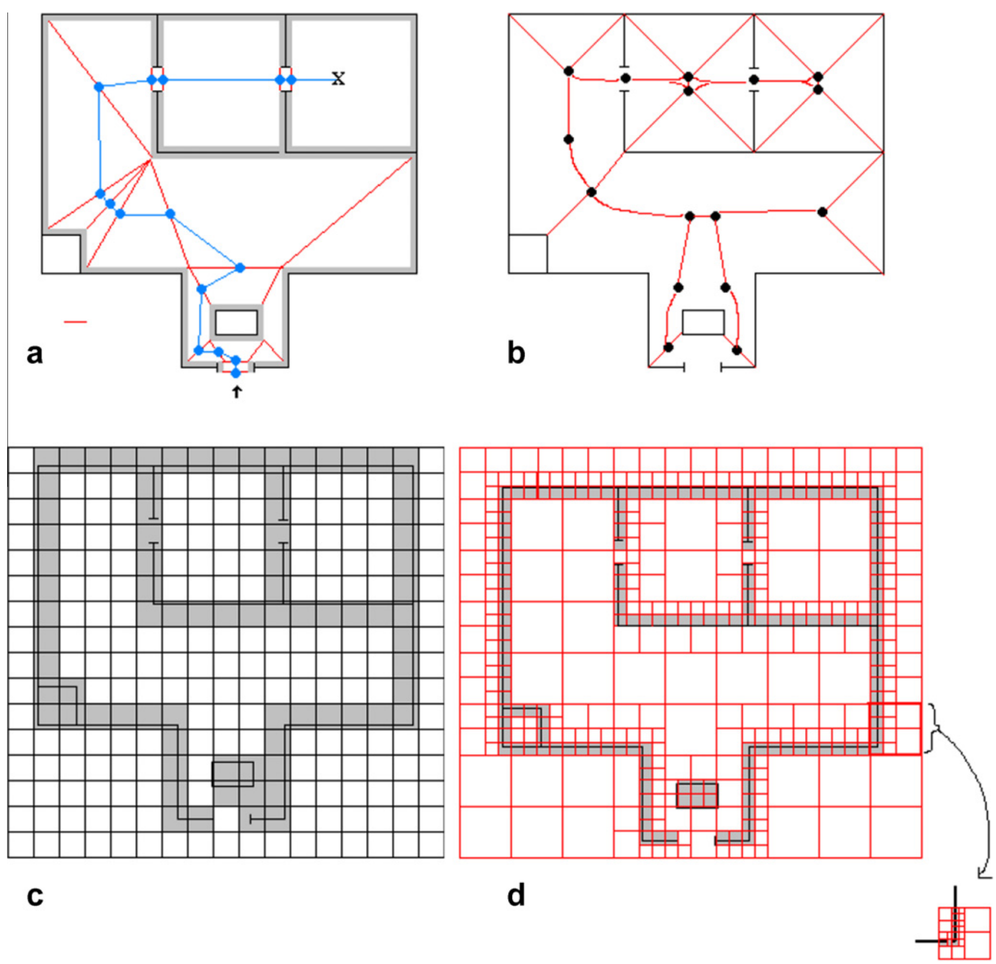

Fig. 5. Mapping illustrations: (a) Meadow Map, (b) Voronoi Diagram, (c) Regular Occupancy Grid, and (d) Quadtree Mapping (Mooney, 2009).

Increasingly, a hybrid mapping method with data reduction is adopted for robot path planning, as in Park et al. (2008). The combination of a topological map and a metric map contains meaningful information about features and objects, whilst being able to use information about relationships between nodes. Another alternative when faced with incomplete environmental data is a Fuzzy Modelling technique, adopted by Zeng et al. (2009) for a dynamic environment in the presence of noise and poor sensor accuracy.

4.4. Guidance and path planning

4.4.1. Line-of-Sight (LOS)

LOS guidance and its variations are still the simplest and most popular guidance laws in use today, particularly in missile guidance technology. The idea behind LOS guidance is that if the vessel converges to a constant LOS heading angle directly between the vessel and target (which may be stationary or moving at a constant heading), then it shall eventually converge to the target position. The LOS angle, ψ_{los} in its simplest terms, is calculated in terms of its current and previous waypoints, p and p_k respectively as defined in Fig. 6,

where (x, y) and (x_{los}, y_{los}) represent the current and LOS coordinates respectively. The *arctan* function yields an angle between $\pm\frac{\pi}{2}$ radians and must be carefully mapped onto the correct quadrant of the full heading angle range.

$$\psi_{los} = \arctan\left(\frac{y_{los} - y}{x_{los} - x}\right) \tag{3}$$

The radius/circle of acceptance is usually proportional to some geometric feature of the vessel, e.g. length or width. The drawback of LOS guidance is potential overshoot caused by reducing the cross-track error due to environmental disturbances (Naeem et al., 2003). Other similar target-tracking laws are mentioned in Breivik and Fossen (2008) which include Pure Pursuit and Constant Bearing guidance.

4.4.2. Artificial potential field

Artificial Potential Field methods take known obstacles into consideration by building a representation of the environment by potential gradients, contrived originally in Khatib (1986). An attractive field is assigned to the target, whilst negative fields represent obstacles and so the vessel is repelled at these locations. The advantages of such a method are effective use in real-time with low computational requirements. However, the primary disadvantage is the potential to get trapped in local minima, resulting in this method being used solely for local path planning in literature. One solution to this problem is proposed in Daily and Bevly (2008), presenting the use of Harmonic Potential Fields, i.e. harmonic functions which do not contain local minima. An illustration of the basic principle of artificial potential fields is provided in Fig. 7 (Lee et al., 2004).

The sum of forces at any location is equal to the vectorial addition of the sum of attractive forces, F^+ and the sum of repulsive forces, F^-.

$$F^+ = -\nabla U^+ = -k|r - R|^2 \tag{4}$$

$$F^- = -\nabla U^- \tag{5}$$

where k is a scalar constant, r is the position vector of the vessel and R, the target position vector. U^- can be calculated using the *Force Inducing on an Artificial Repulsion from the Surface* (FIRAS) method outlined in Khatib (1985), which is dependent upon the range of the repulsive fields' influence.

Another vector field approach is the stream function, borrowed from fluid dynamics to describe the motion of incompressible fluid, accounting for rotation and viscosity. This method has been developed for underactuated vehicles (UAVs) for path generation in complex scenarios such as multiple obstacles, formation control and dynamic path replanning (Sullivan et al., 2003).

Some of the COLREGs guidelines have been implemented with reported success using an extension of this method, named Modified Virtual Field Forces (MVFFs), in addition to fuzzy expert rule based logic (Lee et al., 2004). However, the complete system incorporates over 200 fuzzy rules and presents only single encounter scenarios.

4.4.3. Evolutionary Algorithms (EAs)

EAs are being applied increasingly to path planning scenarios. These algorithms represent artificial intelligence by mimicking evolutionary behaviour of biological systems. They address the problem of multi-objective optimisation where traditional optimisation methods such as gradient descent become too complex or computationally demanding. However, the pitfalls with such methods are once again the potential of getting trapped in local minima, finding at best a near-optimal solution (as the global optimum is never guaranteed) or even failing to find a solution at all in some instances. In addition, these methods are generally restricted to offline implementation. EAs are characterised by a cost, or

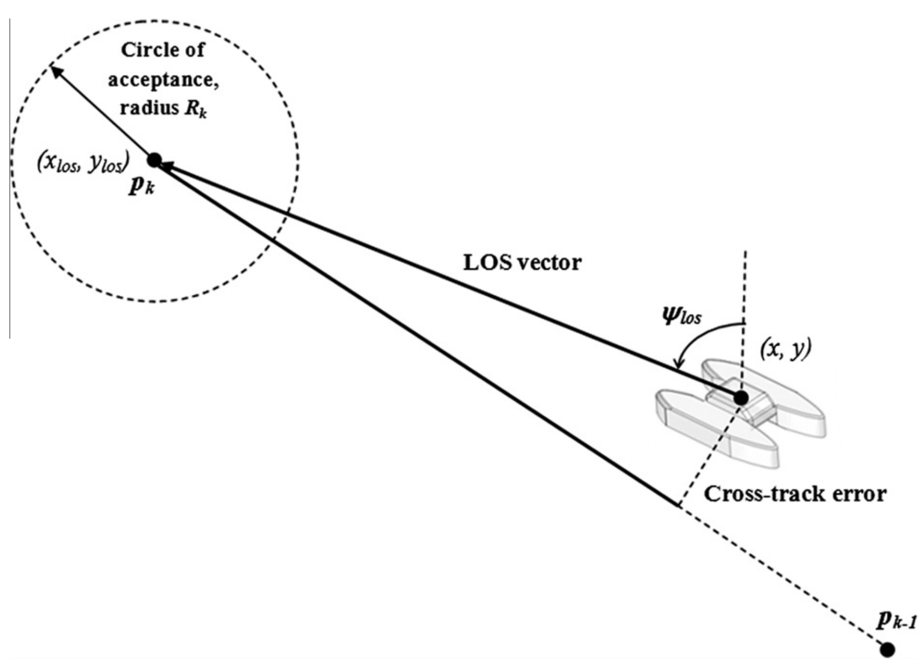

Fig. 6. LOS guidance illustration.

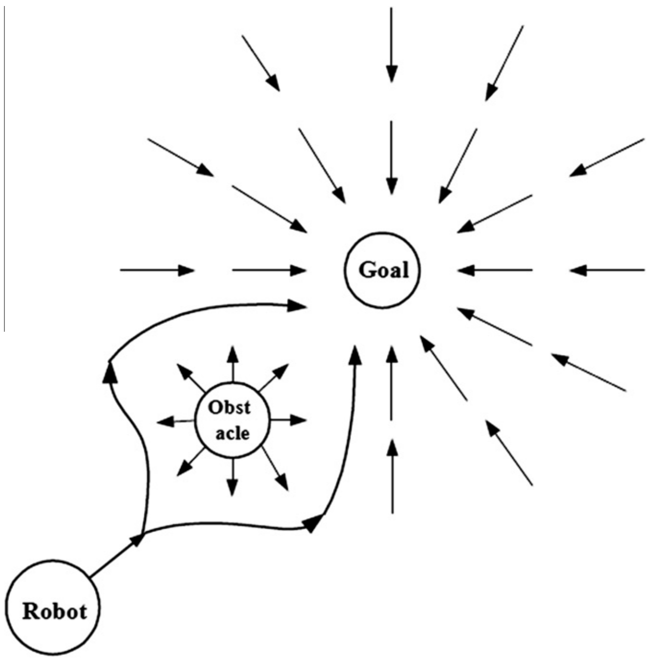

Fig. 7. Artificial potential field concept illustration (Lee et al., 2004).

fitness function which is to be optimised with respect to specified constraints. Genetic Algorithms are perhaps the most common used to date for generating waypoints, as in Kanakakis and Tsourveloudis (2007). Other methods include Ant Colony Optimisation (Zeng et al., 2009) and PSO (Particle Swarm Optimisation) (Li et al., 2006). As with all waypoint path planning techniques, the resulting series of waypoints will form a non-continuous path which would result in jerky motion. The use of splines provides polynomial fitting, applied as smoothing functions.

4.4.4. Heuristic search algorithms

Path planning algorithms are required to generate a sequence of actions (a route) from a start position to a pre-defined goal position. The following group of algorithms belong collectively to a family of grid-searching techniques with associated heuristic cost functions. Due to the grid nature, heuristic search algorithms are particularly prevalent in computer game design. A feasible, near-optimal path is found without performing an exhaustive search, as with uninformed (or blind) graph searching algorithms such as Breadth-first or Depth-first searches. Instead, the search relies on information known about the problem domain or environment, which guides the search more efficiently. A few of the most applicable heuristic algorithms are introduced.

*A*Search Algorithm*: Loosely based on the same principle as Dynamic Programming, developed as a faster alternative to Dijkstra's Algorithm (Dijkstra, 1959), the A* algorithm (Hart et al., 1968) performs a Best-first search of the most probable paths leading to the goal. The cost function takes into account the cost of the path already travelled, to the current node, $g(n)$ and the estimated cost of the remaining path to the target node, $h(n)$. The evaluation function is therefore:

$$f(n) = g(n) + h(n) \tag{6}$$

The advantages of using A* for path planning include expanding only the fewest number of nodes to quickly find an optimal solution which is admissible. However, the main drawback of incorporating pure A* and Best-first searches in general is the large computational memory requirement, leading to difficulties in real implementation. A* has also exhibited inadequate performance in dynamic or partially unknown environments and the cost-function is often difficult to evaluate for complex problems. This has led to the modification of A* algorithms for improved functionality, e.g. IDA* (Iterative Deepening A*) which reduces the memory capacity by retaining information about one path only at a time.

D Search Algorithm*: Alternatively known as Dynamic A*, this algorithm is referred to as a re-planning one. A* assumes that all information about the CSpace is complete and accurate, however in the real world this is seldom the case. "The D* algorithm plans optimal traverses in real-time by incrementally repairing paths to the robot's state as new information is discovered" (Stentz, 1995). Instead of constantly re-running A* from the beginning each time new information is gathered, D* enables only the affected data to be recalculated, as opposed to the entire set of data which is time-consuming and computationally intensive (Ferguson et al., 2005). Other more efficient variations exist in the form of and Focussed D* and D*Lite (Koenig and Likhachev, 2005), which is a modified version of the LPA* (Lifelong Planning A*) heuristic (Likhachev and Koenig, 2005).

Fig. 8 shows the shortest path found by a modified, incremental A* search algorithm for a crossing vessel encounter, where the approaching vessel's position is determined at each discrete time interval. This method has not yet been implemented and is demonstrated for the purpose of this survey. Initially a global shortest-path is computed, then if a vessel is detected within near proximity, the algorithm re-plans the next sub-path segment in real-time, to avoid the approaching vessel and passing aft of the stand-on vessel (in line with COLREGs protocols which are described in the following section). The path is constantly re-planned at each time interval online until the threat has passed. The final path traversed is shown, smoothed using Cubic Hermite interpolation.

Heuristic Anytime Algorithms: Due to time constraints, it is not always possible to generate paths via the afore-stated methods in real-time due to the amount of data processing. Anytime Algorithms were developed to achieve solutions which are as optimal as possible within the timeframe given and so address the time vs. quality trade-off. The solution approaches optimality as time progresses (Zilberstein and Russell, 1995). ARA* (The Anytime Repairing A*) and AD* (Anytime Dynamic A*) algorithms are clearly discussed by the developers in Likhachev et al. (2005).

A recent publication describes the method coined as Homotopic A* (HA*) which searches a homotopy class, creating a reduced search space which has a high probability of containing the optimal solution. A homotopy class is defined as a collection of paths sharing the same start and end points which can be deformed into each other without passing through any obstacles. This has yielded faster results than that of A* and ARA* when tested with an underwater vehicle, *SPARUS* (Hernández et al., 2011).

Evolutionary Algorithms have been combined with heuristic search algorithms to account for the dynamic and time-constrained situations. For instance, (Leigh et al., 2007) makes use of a GAMMA (Genetic Algorithm-Manufactured Manoeuvring Algorithm) to increase the performance of A* to explore paths for increased speed and optimality. New developments in path planning are rapidly emerging in the game development industry. HPA* (Hierarchical Path-Finding A*) is one worthy of mention, which aims to improve the responsiveness of traditional algorithms in large, complex maps (Botea et al., 2004). Data is stored hierarchically, from low-level to high-level planning. Information is never discarded, but is cached and reused to reduce computation.

As previously discussed, A* has limitations when applied to real-time, continually updating problem spaces, as the computational cost rises exponentially leading to inadequate, sluggish behaviour. Artificial Intelligence in computer game technology has been designed to handle such situations by using hybrid

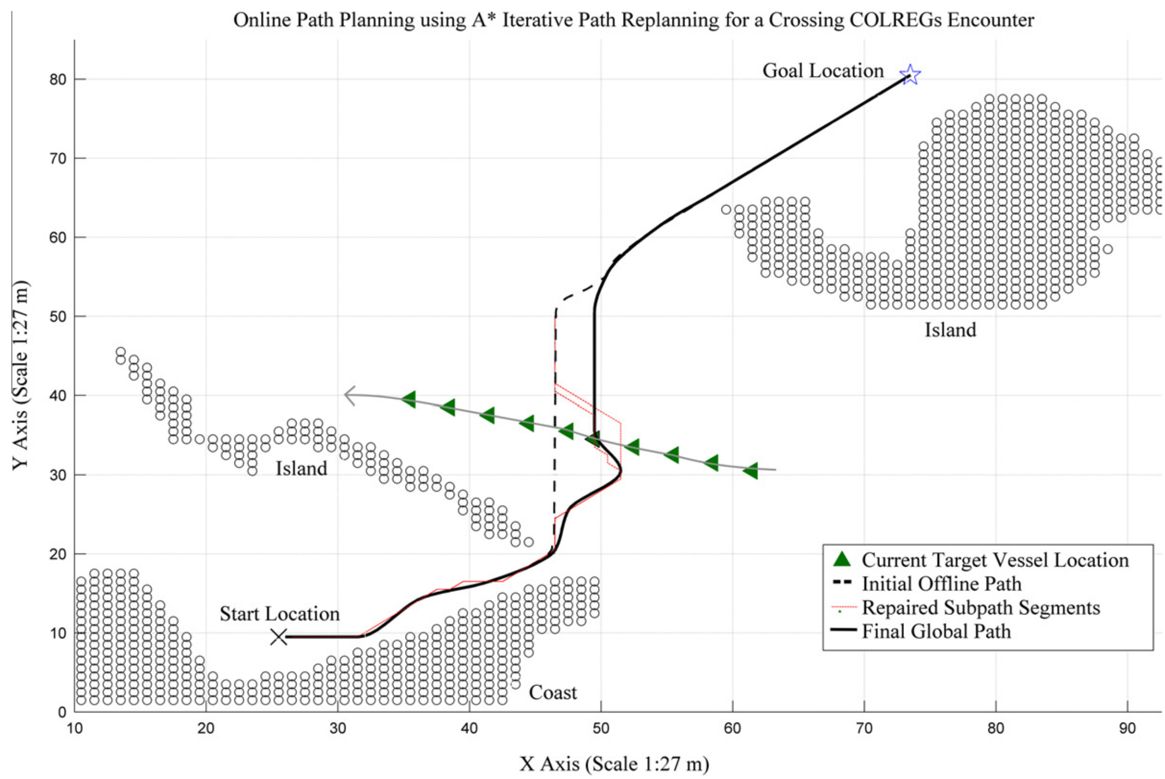

Fig. 8. A* path planning example in MATLAB for crossing scenario on a scaled map of a coastal region near Montijo, Portugal.

combinations of online and offline path planning. One such method is proposed by Guzman et al. (2005) which calculates all possible pre-defined paths offline and stores them in a lookup table. This deals with the static environment motion planning problem. When the current path is blocked by some dynamic obstacle, the A* algorithm will be activated online to find an alternative path to the next feasible cell before reverting back to offline planning. This presents another promising approach to the global path planning case for USVs in a dynamic environment, assuming the map is represented by cell decomposition.

4.4.5. Path smoothing and vehicle dynamics

With the exception of motion planning techniques which encompass vehicle dynamics, i.e. generate only time-parameterised vectors which are feasible for the vehicle to traverse, such as the Dynamic Window Approach for real-time obstacle avoidance (Brock et al., 1999), most of the path planning methods mentioned produce inexecutable paths. The common problem amongst many of these techniques is the failure to produce a smooth, continuous path accounting for the minimum turning radius or turning rate of the vehicle. The resulting path is often described by straight lines joining waypoints, which would result in jerky, non-continuous motion with high turning rates which have the potential to damage actuators. It is therefore desirable to incorporate the dynamic behaviour of the vehicle so that the specified path is suited to the USVs turning abilities.

In order to specify a smooth path, at least the first derivative must be continuous. It is more manageable to deal with subpaths rather than the whole projected path. These paths then merge to form the entire path running through all the waypoints. A popular recurring method found in literature is the use of spline or polynomial interpolation (Fossen, 2011). A cubic spline is a third order polynomial whose second-order derivatives at the endpoints must be equal. A simple example of a path generated using a variation of this method is illustrated in Fig. 9.[2] Polynomial interpolation usually includes higher order polynomials which describe more oscillatory behaviour. The derivatives also give rise to the velocity or acceleration profile along the path. An associated disadvantage with using this approach is that if one of the waypoints changes, the all coefficients and hence the entire path must be recomputed. Although these standard interpolation methods such as β-splines produce a visibly smooth path, they do not truly incorporate specific vehicle dynamics, for instance minimum turning radii.

Much work has been carried out imposing dynamic constraints on paths, for instance the use of Pythagorean hodographs with curvature constraints placed on the waypoints (Farouki and Sakkalis, 1990). Unlike Dubins (Dubins, 1957), which describe the shortest path in terms of composite arcs and straight lines with an intrinsic curvature discontinuity at each boundary, Pythagorean Hodographs produce a single curve with continuity up to the second derivative. Alternatively, Clothoids (Fleury et al., 1993) with a linearly varying curvature are often used to solve the discontinuity problem with equal curvatures at the segment boundaries. Another example is the recently developed Direction Priority Sequential Selection Algorithm (DPSS) which has demonstrated more favourable paths than A*, with better efficiency (Yang et al., 2010). Jerky motion is eradicated by a Path Fin Cutting (PFC) function which optimises the raw path in a smoothing manner. These examples mentioned are just some of the existing methods for obtaining feasible paths in robotic path planning. For application with COLREGs collision avoidance, further constraints must be put upon the paths generated in order to abide by the laws which are introduced in the following section.

[2] The splines example in Fig. 9 was generated using standard MATLAB interpolation functions, ‘spline’ and ‘pchip’.

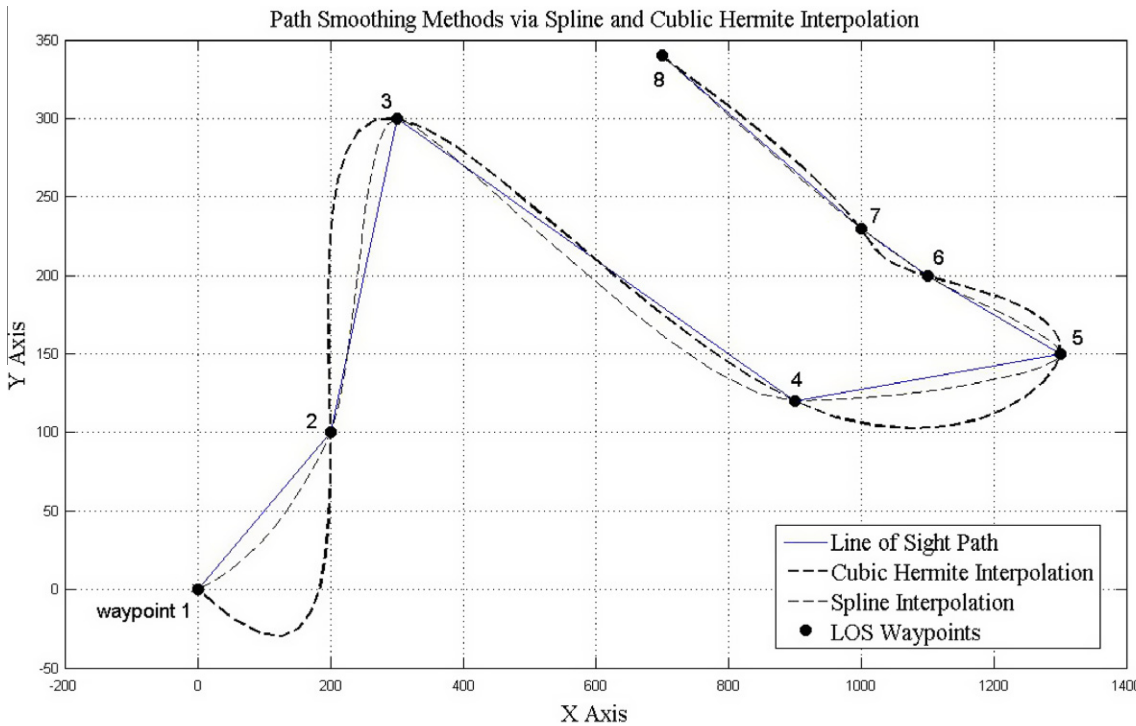

Fig. 9. Cubic spline interpolated path.

5. The International regulations for avoiding collisions at sea

COLREGs were designed to be followed by humans when operating all types of vessels or watercraft. Without a human operator or crew present on the vessel, the rules must still be obeyed if an unmanned ship is to be lawfully operational at sea. Otherwise unpredictable or incorrect actions may lead to confusion and potentially catastrophic collisions amongst other marine traffic. In the case of remotely operated vessels, the operator shall implement all manoeuvring decisions. Conversely, an autonomous vessel should have the ability to make these same decisions based largely on sensor information. The regulations are comprised of three main sections (Commandant, 1999);

- *General (Part A)*: Outlining the applicability and responsibilities of the regulations.
- *Steering and Sailing Rules (Part B)*: Part B consists of two sections, where Section 1 refers to the conduct of vessels in any visibility conditions and Section 2 regards the conduct of vessels in sight of one another.
- *Lights and Shapes (Part C)*: Covers protocols for issuing indicating, warning or distress signals, etc. and safe guidelines for the use of lighting.

Although rules from all sections are applicable, the *Steering and Sailing Rules*, in particular of vessels in sight of one another present perhaps the greatest challenge for implementing full autonomy. Some of these main rules are listed below.

- **Rule 13 – Overtaking**: *Any vessel overtaking any other shall keep out of the way of the vessel being overtaken.*
- **Rule 14 – Head-on Situation**: *When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other.* See Fig. 10.
- **Rule 15 – Crossing Situation**: *When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.* See Fig. 11.
- **Rule 16 – Action by give-way vessel**: *Every vessel which is directed to keep clear of another vessel shall, so far as possible, take early and substantial action to keep well clear.*
- **Rule 17 – Action by stand-on vessel**: *Where one of two vessels is to keep out of the way, the other shall keep her course and speed. The latter vessel may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these rules.*

Rule 18 specifies which type of vessels must be prioritised when giving way, depending on the type of craft in question, e.g. a power-driven ship must always keep out of the way of a sailing boat. The guidelines in *Part A* must also be taken into consideration, for example maintaining a safe speed and taking action when entering narrow channels. The sound and lighting protocols detailed in *Part C* can be integrated within the obstacle avoidance routines for indicating and issuing warnings, as well as emergency action, or fail-safe methods when another vessels or dynamic objects behave in an unpredictable manner.

An example of a low level behavioural scheme is provided in Fig. 12 as a flowchart which considers COLREGs based encounter scenarios only.

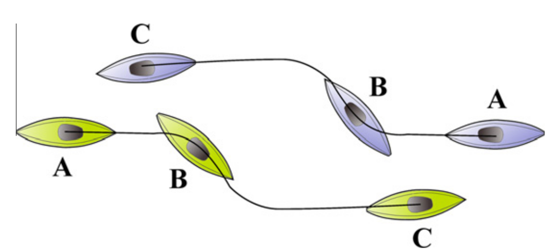

Fig. 10. COLREGs Rule 14: head-on situation.

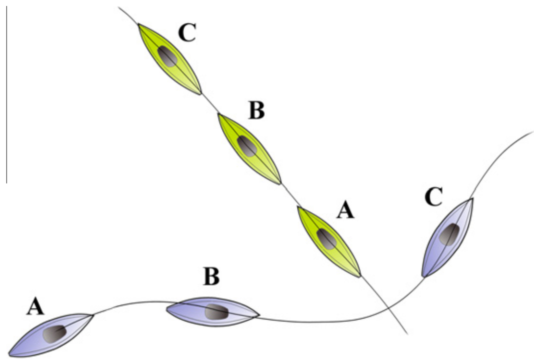

Fig. 11. COLREGs Rule 15: crossing situation.

The manoeuvres associated with COLREGs will require substantial preplanning as part of deliberative avoidance. However the response heavily depends on the state and actions of the other ship and so manoeuvring decisions must be made online. If the encounter situation is not covered by the standard deliberative avoidance or COLREGs avoidance protocols, then the reflexive avoidance module must ensure that collision does not occur. For example, a high speed vessel approaching head on makes a turn towards port instead of starboard and comes within an unsafe distance. The USV should take avoidance action to avoid collision at any cost, as COLREGs exceptions will inevitably occur where safety is paramount. The operator may not have been able to successfully intervene in time to prevent a collision, and so the automatic obstacle avoidance system takes over.

Collision risk assessment is vital before the vessel makes any course changing decisions. As described in Karmarkar and Vargus (1980), the risk assessment must determine the closest point of approach (CPA), the corresponding time to the closest point of approach (TCPA) and a projected area of danger (PAD), by extrapolating the other vessel's position with time. Fig. 13 defines two circles, whose radii depend on the geometry of the vessel. The *circle of avoidance* with radius, R_a lies inside the sensor range and assesses the initial risk of collision. If the other vessel lies outside of this circle and is hence a reduced threat, the USV need not take any avoidance action. Once inside the *circle of avoidance*, the ship should anticipate and then execute the correct manoeuvres based on the predicted course of the other vessel. If at any time the other vessel comes within the *critical safety circle* of radius, r_s, there is a substantial risk of collision and so the avoidance scheme shall be switched to reflexive evasion.

6. COLREGs for multiple unmanned vessels in cooperation

Due to the considerable attention given to the topics of multi-vehicle cooperation and formation control in recent years, it would be incomplete to consider the broad area of USV obstacle avoidance without reference to a fleet of cooperating USVs. This is a difficult and challenging topic which has generated significant interest. However due to its complex nature, the implementation of cooperative COLREGs has yet to be researched. The cooperative control problem concerns a fleet of unmanned ships navigating to a target location, whilst maintaining a formation pattern and successfully avoiding obstacles. A detailed explanation of the concepts of multiple agent control and cooperation can be found in Balch and Arkin (1998) and Murray (2007), which also outline commonly implemented formation control methods. This survey considers the practicalities of cooperating vessels in relation to COLREGs. No single solution exists to the cooperative multi-vessel issue in terms of motion planning. The first consideration in contriving a solution framework is establishing the application and mission requirements in order to assign appropriate protocols.

Working unmanned vessels have become a prominent tool in military strategies. Naval vessels in cooperation are responsible for minesweeping, surveillance and rendezvous missions amongst others, with the benefits of increased sensor coverage and task efficiency, i.e. delegating individual tasks to each member to achieve a collective goal. Naturally, in military zones COLREGs are extraneous and are therefore disregarded. Even during transit in neutral waters, COLREGs are not particularly applicable, due to enforced naval vessel protection zones. The military fleet will always act as a stand-on unit and all other vessels must maintain a sufficient clearance and stop if necessary. However, COLREGs must still be applied during research missions, particularly because the unmanned vessels are typically small in size and thus are often forced to give way to large cargo or passenger ships. This type of application is usually related to oceanographic research and environmental sampling and may additionally include underwater vehicles within the network. The ideal strategy for vessel-fleet encounters would be to avoid the oncoming vessel as a single, rigid unit, if the swarm maintains a tight formation. However, as the distance between each vessel increases, it may be necessary for one or more vehicles to perform independent COLREGs avoidance manoeuvres without affecting any other member of the team. This will certainly be the case in exceptional circumstances, for instance, if an oncoming vessel has failed to observe the multi-vessel network, despite AIS transmission, and breaches the formation. It is vital that precautions are taken to prevent inter-vessel collision between cooperating individuals.

The next crucial consideration is selection of the formation pattern and the reference behavioural scheme selected. Line, column, diamond and wedge are amongst the most popular geometric formation patterns, each being suited to specific referencing schemes. *Unit-centre*, *leader-referenced* and *neighbour-referenced* approaches are described in Balch and Arkin (1998). The use of a centralised system to receive data and allocate commands is beneficial in terms of efficient and seamless operation. Vessel control may be of a centralised or decentralised nature. Distributed control, where each vessel is responsible for determining its own actions based on observations may cause conflict within the group. Centralised systems characteristically exhibit improved coherence and have the ability to make provision for individual behaviours in a more informed sense. The disadvantage is of course the computational demand required to do so.

The group should collectively track a virtual trajectory as in Vanni and Aguiar (2008), or simply a spatial path with constant velocity adjustments in order to maintain the formation pattern. The fleet requirements include:

- Maintaining formation at all times unless safety or efficiency is compromised during an encounter scenario.
- Avoiding all obstacles, i.e. geographical features and oncoming vessels, using COLREGs where applicable.
- Preventing inter-ship collisions.
- Avoiding a deadlock situation, where the movement of one or more vessels is prohibited due to the spatial positions of other vessels in the fleet.
- Avoiding waiting or coming to a full stop due to vessels lagging behind.
- Behaving as a stand-on unit in all encounter situations, except in extenuating circumstances, e.g. when approaching an oil tanker which cannot deviate from its set course without great difficulty.
- Exhibiting a robust control system which functions adequately in the presence of lag and errors.

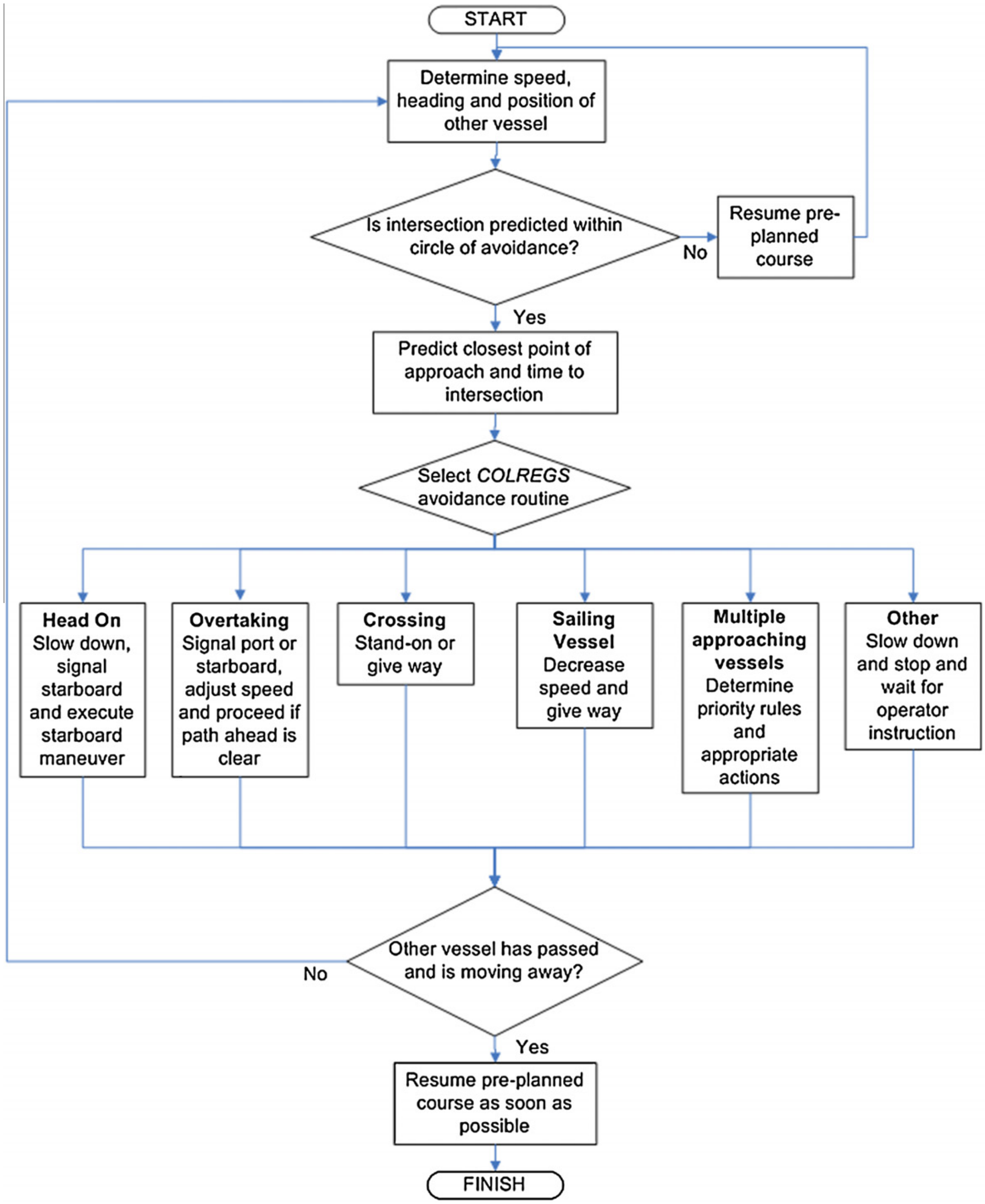

Fig. 12. COLREGs behavioural flowchart.

The nature of this cooperative vehicle problem is a multi-objective one, which requires a high-level decision-making framework which can deal with complex interactions and prioritise the primary objectives. Strategies such as MILP have been suggested (Murray, 2007) to deal with problems of this nature, although not pertaining to COLREGs as an additional constraint. The behaviour of the fleet must be optimised with regards to safety (as priority), adherence to COLREGs and efficiency in terms of total distance travelled and total changes in speed. Three main behavioural subsets can be described for encounter situations with a cooperative group of USVs. These are outlined in Fig. 14. Switching between behavioural types should be as seamless as possible, where vessels can take early and substantial action, having first verified the feasibility of the action decided upon.

7. Discussion

The COLREGs guidelines have been implemented with some success using the MVFF and fuzzy logic method discussed previously for simulations of the main encounter scenarios when confronted with single vessels only (Lee et al., 2004). Encountering multiple vessels poses a more difficult challenge, which incorporates multiple rules and more than one unique solution to the avoidance problem. A very simple approach considers only one

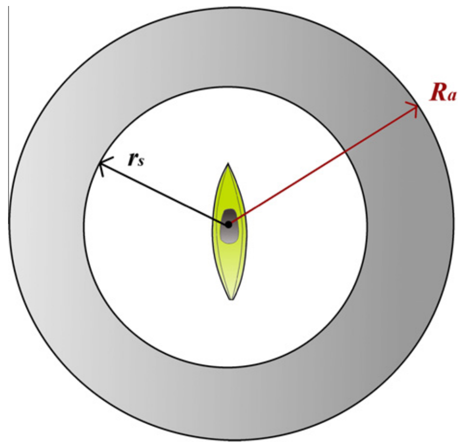

Fig. 13. Definition of circle geometry.

single vessel within close range, which is dealt with as a priority according to COLREGs, followed by the second vessel at longer range, should it cross the *circle of avoidance*. If all traffic is within close range, the USV may slow down and remain stationary until a maximum of one single threat remains, or alternatively switch to reflexive avoidance only, however this is a poor and inefficient solution in highly congested waters. An improved solution is proposed by Benjamin et al. (2006) which attempts to mimic human behaviour by averaging the action of two compatible rules. For instance, it may be feasible to implement head on and crossing manoeuvres at the same time, but the combination of others may be contradictory or mutually exclusive, such as those requiring conflicting stand-on and give-way actions. The appropriate action is sought via priority weighting with Interval Programming. However the resulting system has not been deemed fully *COLREGs compliant*. Fuzzy behaviour learning is often adopted in such situations where a system is required to imitate human-like thinking and thus could be investigated for this multi-vessel encounter problem. The review in Tam et al. (2009) discusses the idea of ship domain models with defined sectors for assessing and categorising encounter types which aids the avoidance rule selection.

As mentioned before, heuristic and evolutionary methods have been used extensively for deliberative path planning. Several studies have successfully incorporated basic COLREGs avoidance rules based on modified A* (Casalino et al., 2009), ACO (Tsou and Hseuh, 2010) and trajectory selection according to a multi-stage selection process which considers a range of criteria in terms of safety and performance (Tan et al., 2010). Whilst these methods may prove effective for static and dynamic obstacles in simulations, there are prevalent issues with efficiency. For real-time implementation, a near-optimal solution is usually satisfactory in order to conserve computation time. However for a dynamic environment which is constantly changing, efficiency remains an issue with these

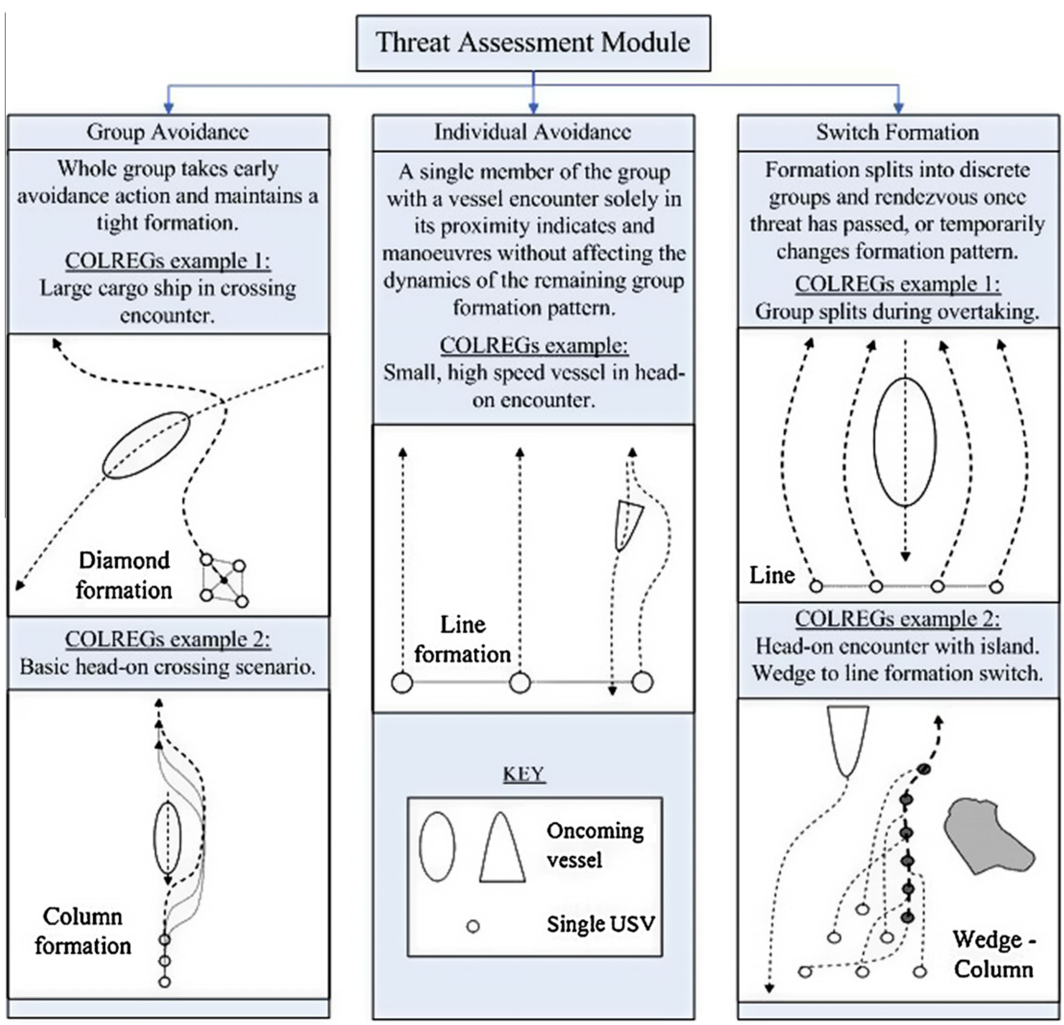

Fig. 14. Behavioural strategies for COLREGs avoidance.

standard algorithms, as much information is discarded with each iteration which results in the necessity to search the entire solution space on many occasions where only local path replanning is required. Further modifications of existing algorithms should be attempted in order to retain as much information about the environment as possible and reduce computational requirements.

Reactive avoidance is discussed to a lesser extent throughout the literature concerning COLREGs avoidance. The potential field method is adopted for static and dynamic obstacles with simulations for single and multiple vessel encounters exhibiting correct crossing and head on avoidance behaviour (Xue et al., 2009). Another reactive technique which has been investigated for this purpose is based on the Distributed Architecture for Mobile Navigation (DAMN), selecting an appropriate arc to follow based on individual weighting according to its intersection with obstacles. In order to deal with moving obstacles, the future ship positions are projected and the velocity is first adjusted in an effort to avoid collision via the Velocity Obstacle Method as described in Larson et al. (2006). Well-documented problems with reactive avoidance methods such as these include sporadic or unpredictable behaviour when switching between path selections or receiving conflicting signals and the possibility of getting trapped between static obstacles, inlets or other geographical features with no means of resuming course. Therefore without improvement, these techniques are not practical standalone methods for collision avoidance.

One of the afore mentioned reviews (Tam et al., 2009) identified three main deficiencies with the research contributions to date. The first is no consideration of environmental factors or the mission profile-related constraints. Additionally, highly simplified USV models are often used with idealised dynamics such as constant speed. It also comments that the dynamic obstacles which are often considered are not truly dynamic, but only partially dynamic. This can be assumed to mean that simulated obstacles exhibit regular motion such as constant speed and heading, and often stand-on in encounter situations without altering course. In reality, a target vessel's motion can never be predicted and so the ODA system should be capable of dealing with more varied and unique encounters.

Work has been done on modifying the standard A* heuristic search algorithm for real-time path planning, incorporating COLREGs avoidance rules for a USV, as illustrated in Fig. 8. Here an initial global path is calculated offline and, when an approaching vessel is detected within a specified proximity, a heuristic algorithm automatically 'repairs' the affected path segment incrementally to incorporate COLREGS obstacle avoidance, according to the target vessel's projected temporal position. This incremental algorithm can be made increasingly efficient, via modifications inspired by LPA* and D*Lite, which re-use previously known cost information of unchanged nodes. A decision-making module determines the relevant COLREGs encounter scenario, and automatically adds the 'forbidden' regions to the closed list, e.g. a set of starboard coordinates if vessels must pass port-to-port. A decision-making system (for instance using MILP) is also capable of adjusting the vessel speed during waiting and manoeuvring. The resulting path will require the incorporation of dynamics, which are unique to each vessel. Dubins, Clothoids and Pythagorean Hodograph methods shall be investigated for producing traversable paths in terms of turning radii.

Full COLREGs compliance is clearly challenging to implement for an autonomous vehicle, as it must exhibit intelligent behaviour in order to interpret and execute these rules designed for humans. The decision-making abilities of the USV are only as good as the data provided by the sensors regarding the state of the other marine traffic, and the predictions of their respective trajectories. However, recent developments in sensor technology allow fully autonomous USVs to come one step closer to reality, without the need for such laborious and costly operator supervision and intervention. Apart from the stand-on scenarios mentioned in *Rules 14 and 15*, it is advisable that an autonomous vessel should always give way to other traffic if in any doubt. For example, a container ship with a turning radius of up to a mile is always realistically the stand-on vessel and cannot be expected to deviate from its course in order to avoid a small unmanned ship. This highlights the need for adequate perceptive abilities, in terms of the classification of obstacles and ships in the vicinity, their current and future states and hence the selection of the most appropriate course of action.

8. Conclusion

This review has discussed the current state of USV collision avoidance research in terms of control, path planning and collision avoidance architecture with regards to COLREGs incorporation. The *USV Master Plan* has provided the research community with an additional incentive which defines the research direction for the future regarding increased autonomy. Until now, the limited capabilities concerning judgement, reasoning and planning have prevented the establishment of the necessary legal policies for USVs or any scope for their acknowledgement within COLREGs guidelines.

One of the primary weaknesses identified with USV ODA systems to date include the inability to deal with complex encounter scenarios which require human-like thinking to select an appropriate course of action, as opposed to a single discrete action. A challenge also exists in quantifying the complete set of qualitative COLREGs protocols, which were intended for human comprehension.

A fully COLREGs compliant USV has the potential for a wide range of applications in civil, military or research applications, all of which require safe navigation in open waters. The obstacle avoidance system demands effective sensing and detection performance in order to determine the state of all objects in the vicinity. The controller should ideally exhibit trajectory tracking abilities in the presence of environmental disturbances, which are required for the necessary avoidance manoeuvres. In terms of path planning, a balance is sought between computational requirement and time for execution whilst operating in real-time, using a combination of online and offline techniques. It is important to account for the dynamics of the specific vessel when planning these paths. In order to deal with a variety of static and dynamic obstacles which are not known *a priori*, the obstacle avoidance architecture should include protocols for deliberatively avoiding objects within the sensor range in an appropriate manner. Marine traffic must be identified as such, and evaded in accordance with COLREGs, whereas it may be inefficient to deal with a stationary island in the same fashion. The ability to handle emergency scenarios or unforeseen circumstances is vital, emphasising the need for some reactive avoidance routine to ensure safety.

Many of the notable contributions discussed provide a promising basis for further development of NGC systems. The synthesis and variations of these existing techniques can serve the objective of bringing USVs to the next level of autonomy.

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Sable Campbell, born in Belfast, Northern Ireland, is a PhD researcher from Queen's University Belfast from the Energy, Power and Intelligent Control (EPIC) research cluster within the department of Electrical Engineering, Electronics and Computer Science (EEECS).

Sable graduated in 2010 from Queen's University Belfast with a Masters degree in Mechanical & Manufacturing Engineering with a 1st class honours. Also a Certified Associate in Project Management, in 2010 she led a team in a Prime Minister's Initiative (PMI2) project in Tsinghua University, Beijing based on sustainable energy.

Her current research interests include marine robotics, path planning, heuristics and control.

Wasif Naeem BEng (1st), MSc, PhD, MIET is a Lecturer in Electrical and Electronic Engineering at Queen's University Belfast. Prior to that, he was a postdoctoral research fellow in autonomous vehicle control at the University of Plymouth (UoP) to develop navigation, guidance and control algorithms for an unmanned surface vehicle. His doctoral research, also at UoP, involved developing an autonomous underwater vehicle in collaboration with Cranfield University, Subsea7, QinetiQ and South West Water Plc.

His current research involves intelligent path planning, multi-vehicle formation control and collision avoidance strategies for marine vehicles with an emphasis on marine rules of the road. He is a member of IFAC technical committee on marine systems, IET and has been the steering and program committee member of a number of international conferences. His research interests span autonomous systems, optimal control, system identification, process control and systems engineering. Dr Naeem is the author of over 45 peer-reviewed journal and conference papers and two book chapters. Two journal papers were awarded the Michael Richey Medal and the Denny Medal in 2008 and 20010 respectively.

George Irwin is a 1st class honours graduate in Electrical and Electronic Engineering (1972) from Queen's University Belfast. He also obtained a PhD in Control Theory (1976) and a DSc (1998) from the same University. He has held a personal Chair in Control Engineering since 1989 and has just retired as Research Director of the Intelligent Systems and Control cluster.

Prof Irwin is a Fellow of the UK Royal Academy of Engineering, Member of the Royal Irish Academy and was recently elected a Fellow by IFAC. He is also hold Fellowships of the IEEE and the UK Institute of Measurement and Control. International recognitions include Honorary Professorships at Harbin Institute of Technology and Shandong University, and is a Visiting Professor at Shanghai University.

Prof Irwin's research covers identification, monitoring, and control, including neural networks, fuzzy neural systems and multivariate statistics, much of which involves industrial collaboration. His most recent personal contributions have been on wireless networked control systems, fault diagnosis of internal combustion engines and novel techniques for fast temperature measurement. He was Technical Director of Anex6 Ltd., a University spin out company specialising in process monitoring and has some 350 research publications, including 120 peer-reviewed journal papers. George Irwin has received four IEE Premiums, a Best Paper award from the Czech Academy of Sciences and the 2002 Honeywell International Medal from the Institute of Measurement and Control.

He is a former Editor-in-Chief of the IFAC Journal Control Engineering Practice and past chair of the UK Automatic Control Council. As well as service on a number of IFAC technical Committees, he has chaired the IFAC Awards and Publications Committees and is currently a member of the Publications Management Board. He received an IFAC Distinguished Service Award in 2008.