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Fundamental principles of passage planning for autonomous vessels

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Abstract

This article aims to depict the fundamentals of passage planning and route management for an autonomous vessels (AV). It presents a derivation of such a voyage passage plan, its step-by-step analysis, and a comparison to its conventional equivalent. This passage plan consists of four major parts: dock and harbour, en route, approach, and mooring stages. The whole activity of passage planning itself may be divided into the following stages: appraisal, planning, execution, and monitoring. The paper concludes with an overview of potential future applications and use of mentioned content.

Introduction

According to a report published by insurance company Allianz (2012), between 75 and 96 percent of marine accidents result from human error. This is often a result of fatigue (Allianz, 2012). Remote controlled and autonomous ships are not at risk of fatigue and hence their use will reduce the risk of injury and even death amongst ships' crews and the potential loss or damage of valuable assets.

According to the president of Rolls Royce, Mikael Makinen, autonomous shipping is the future of the maritime industry. As disruptive as the smartphone, the smart ship will revolutionise the landscape of ship design and operations (Rolls Royce, 2016). Remote controlled and autonomous vessels can be designed with a larger cargo capacity, better hydrodynamics and less wind resistance. With no crew to accommodate, certain features of today's ships can be removed, for example, the deckhouse, the crew accommodation and elements of the ventilation, and heating and sewage systems. This will make the ship lighter, cutting energy and fuel consumption, reducing operating and construction costs, and facilitating new designs.

Unmanned ships have the potential to be more efficient, reduce emissions, and operate at lower cost. However, this will require the effective integration of sensors and improved decision-making algorithms (The Maritime Executive, 2017). As a consequence, an autonomous general cargo vessel might reduce transport costs by approximately 20% compared to a more traditional vessel (World Maritime News, 2017).

The importance of passage planning

There are many modern approaches to the process of passage planning. Some of them are based on special variants of the Orienteering Problem (OP). Solutions for OPs are sets of optimal routes, satisfying constraint conditions such as length or time of travel and consist of the optimal points (with the highest value of some kind of ranks). A ship's passage may comprise of several encounters with potentially dangerous situations, such as navigation in restrained waters, heavy traffic, and severe hydro-meteorological circumstances. In order to maintain the safety of the route, an organisational tool is introduced, which is a voyage plan. Based on the International Maritime Organization (IMO) resolution A.893(21), it is compulsory for the ship's crew to create a voyage plan and use it to control the voyage and passage of the vessel (IMO, 2000). The annex to SOLAS does not offer a specific definition of the plan; nonetheless, it proposes that it contain key elements as follows (IMO, 2015):

- Appraising all relevant information;
- Planning the intended voyage;
- Executing the plan taking into account the prevailing conditions;
- Monitoring the vessel's progress against the plan continuously.

Thus, we propose the following definition of a passage plan: it is a document generated through careful planning of the vessel's voyage, which fulfils the pre-set operational aims for the vessel.

In the first part of the passage planning, which is labelled as the appraisal, the main task of the bridge team is to gather and analyse all information potentially relevant to the route from the point of commencement to the point of destination. This part often is based on a document called Voyage Instruction that is received from the owner/operator of the vessel. They decide which tasks the vessel shall seek to accomplish, on that basis the physical route is generated. The Master's main role is to divide the route into three main sections, the first and the last being harbour entrance piloting passages and the middle being a deep sea and ocean navigation period.

The second part of the passage planning, which is labelled as the planning itself, is the actual set of activities focused around deciding how the passage is to look. The officer responsible for this section (usually the second mate) takes into account the owner's notifications and standing orders in order to meet all the criteria while developing the plan. Required charts are prepared by plotting all courses to be followed on them. The finalized document tends to have a table form and contains a brief summary called the Passage Plan Abstract. Generally, a passage plan consists of a few distinct parts. These parts, as well as their subparts, are presented in the list below:

1. Organisational data category:
   a. name of the vessel,
   b. ports of departure and destinations,
   c. deadlines and important dates;
2. Internal data category:
   a. ship's particulars,
   b. ship's manoeuvring data,
   c. draft survey information,
   d. loading requirements,
   e. crew particulars,
   f. calculation apparatus;
3. External data category:
   a. thorough information on the intended passage,
   b. nautical information sources,
   c. charts and publications,
   d. data required for calculations;
4. Voyage plan;
5. Voyage plan abstract;
6. Voyage monitoring category.

The third part of the passage planning, which is labelled as the execution, should determine the tactics that are to be employed throughout the passage. During this process, the many values regarding the ship constantly change as the vessel advances in the passage. Hence, the risk assessment is to be scrupulously executed and maintained at all times. The personnel, passengers, and cargo require constant scrutiny of the Master to ensure safety and security. Individual problems may arise and thus require immediate yet professional attention.

The fourth part of the passage planning, which is labelled as the monitoring, requires the plan itself to be constantly kept under the scrutiny of the bridge control team. It is a continuous process of checking whether the vessel is proceeding according to the plan. The checking is conducted by various means, such as using pre-installed bridge equipment.

Conventional passage plan

A passage plan is required by the rules. Usually, the main part of the plan is a table containing a list of waypoints (WP).The following data are connected with each WP:

- Position (i.e. latitude and longitude);
- Course and distance to the next WP;
- Distance To Go (DTG) – distance to the last WP;
- Planned speed (usually charter speed) and time required to reach next WP;
- Type of navigation between WPs (i.e. Rhumb line (RL) or GCgreat circle (GC));
- Planned maximum cross track error (XTE);
- Required Under Keel Clearance (UKC);
- Position fixing method;
- Frequency of position fixing;
- Name of WP, additional information (i.e. report to VTS, consecutive number etc.).

There is also other information connected with the route plan:

- Port/harbour data, including communication channels;
- Reporting points, including communication channels and required data;
- Pilot information;
- Charts to be used during passage;
- Publication to be used during passage etc.

A/m table is usually divided into three parts:

- Leaving the dock and harbour area;
- The en route portion of a voyage;
- Approaching the destination and mooring.

An example of the first part is shown in Figure 1.

This part is characterized by frequent course changes, short distances between WPs, and high frequency of positioning fixing. During this part of the voyage, a vessel is usually boarded by the pilot. The same situation refers to the last stage of voyage, i.e. approaching the destination and mooring, while the en route portion of a voyage is characterized by relatively large distances between WPs, and low frequency of positioning fixing (once per hour). During the first and last part of the voyage, only RL navigation is in use, whereas during the second part both options (i.e. RL and GC) are used.

In our opinion, this part of the voyage can be executed autonomously by a vessel with the technology available now. We argue that most of the autopilots which are commonly in use have an option like "Steer To Track" or "AutoSail", which enables ship pilots to keep the vessel on a planned route delivered from the GNSS receiver or the ECDIS. Using such an option, the vessel can easily navigate long distances through open waters. The main challenge is to avoid dangers when they arise. As the voyage plan can be verified during planning or checking process, which is executed before the voyage, dangers connected with grounding can be omitted. Thus, the danger list consists of floating objects, i.e. ships or other large floating debris. Avoiding collision with ships can be achieved through the use of anti-collision systems like NAVDEC (www.navdec.com) (Pietrzykowski, Wołejsza & Borkowski, 2017). An area of heavy weather can be treated as a floating object, and hence the avoidance of it can be accomplished in a manner similar to that of avoiding other ships by a safe distance. The location of the ships are known from AIS or radar; the location of heavy weather areas is delivered from satellite observation. The question is how to detect floating objects, which have no AIS transponder and are difficult to detect by radar (i.e. floating containers, whales, icebergs, recreational boats, etc.) (Pietrzykowski, Borkowski & Wołejsza, 2012).

Passage planning for autonomous vessels

The act of planning a single passage is a complex activity that requires vast knowledge from the Master, namely:

- navigational methods used in voyages;
- areas of ships operation;

Vessel Name	[redacted]	Voyage no.	17A	Date / Time	21-Oct-11
Voyage Info.	- -	From	DAGENHAM	To	DORDRECHT
Vessel's Draft For/Aft	F=6.30m A=6.70m	Voyage Stage		3 - Port Out	

No.	Place Name / Geographical Name	Latitude & Longitude	True Co.	Dist. (nm)	DTG (nm)	Fix method	Fix Freq (min/hr)	Chart Nos./Relevant T&P notices & Nav.warnings / Environmental issues/ Additional Comments / Air Draft / Miscellaneous Route Leg Info.
15		51 - 27.51 N 0 - 17.23 E	52	0.2 nm	27.6 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
16		51 - 27.63 N 0 - 17.47 E	27	0.5 nm	27.4 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
17		51 - 28.10 N 0 - 17.86 E	70	0.4 nm	26.9 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
18		51 - 28.25 N 0 - 18.53 E	108	0.3 nm	26.4 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
19		51 - 28.14 N 0 - 19.05 E	145	0.4 nm	26.1 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
20		51 - 27.80 N 0 - 19.44 E	154	0.6 nm	25.6 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
21		51 - 27.24 N 0 - 19.88 E	136	0.3 nm	25.0 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
22		51 - 27.02 N 0 - 20.22 E	110	0.3 nm	24.7 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
23		51 - 26.92 N 0 - 20.66 E	91	0.9 nm	24.4 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
24		51 - 26.90 N 0 - 22.04 E	88	1.8 nm	23.6 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
25		51 - 26.96 N 0 - 24.99 E	74	0.6 nm	21.7 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures
26		51 - 27.14 N 0 - 25.98 E	45	0.6 nm	21.1 nm	Auto Plot	1 min	T&P,Nav.Warning encluded in Ecdis weekly update/Monitor Pilot commands,Observe Company Piloting Procedures

Figure 1. Example of a conventional voyage plan (Cockrill, 2012)

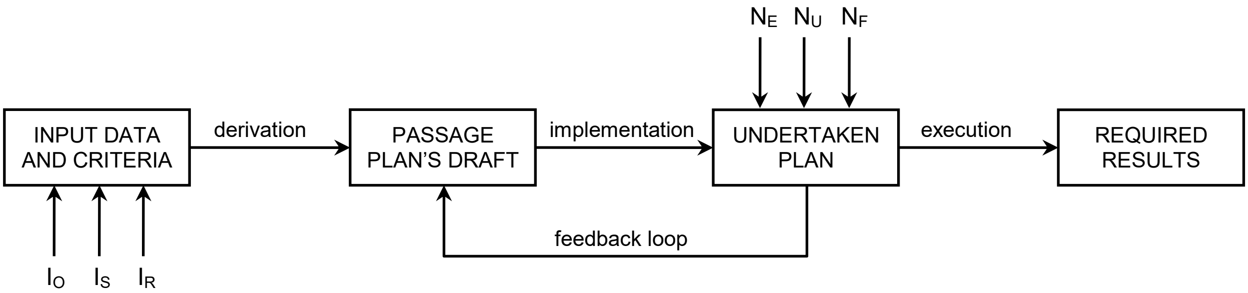

Figure 2. Block algorithm of passage planning

- ship's nominal particulars and its current condition;
- possible and anticipated hydro-meteorological conditions.

However, the main aim of the paper is to develop an algorithm that may enables the generation of a valid passage plan that logically corresponds to the aforementioned criteria. The process may be theoretically divided into three complementary parts: derivation, implementation, and execution. Their relation is shown in Figure 2.

The first step, namely derivation of the passage plan, requires a profound set of data. As shown in Figure 1, it is crucial to include:

- information on the owner's standing orders and requirements (I_O);
- information on ship's particulars, conditions, and limits (I_S);
- information on expected results of the passage (I_R).

In order to be comprehensible for the program, those data must be converted initially into mathematical language and then translated into appropriate source code for an algorithm to operate on. For instance, an owner's order of maximal fuel reservation combines with another set of data, fuel consumption formulas, which are specifically defined for that vessel. Then again, velocity must comply with other rules, the fuel dilemma notwithstanding, such as safe speed or achievable speed.

The second part of the algorithm is the implementation of the passage plan's draft, which is received upon successful implementation of input data into optimization software. However advanced, the software-based algorithms may not always predict all forthcoming events; consequently, between an executed and draft plan a feedback loop is implemented. Its presence aids the debugging of the algorithm and correcting it, should any error occur. On the other hand, it is vital for adapting to current circumstances. That is why in this section three theoretical sources of other information are proposed. Yet unknown, they are necessary to ensure that a maximal possible amount of the passage is rendered safe. Hence, it is crucial to explore:

- the necessity of predicting possible encounters (N_E);
- the necessity of approximating unknown events (N_U);
- the necessity of implementing a way to include fluctuations of already included data (N_F).

The first category includes a ship's encounters, navigational warnings, and other navigation-related dynamic items. The unknown events are hazardous and harmful situations that are unlikely to occur, but in the event that they do, there must be a built-in procedure to include them in the further execution of the plan. The last group comprises hydrometeorological conditions, traffic density, icing, alterations of owner's orders, etc. There are factors that are even not yet briefly described and thus are object to further research (Ostrowski et al, 2017).

The third part of the algorithm, the execution, is to lead to expected results. Only if the outcome is at least bearable the passage may be deemed to have been positive. If any difficulties are encountered, their temporary and permanent remedies are to be recorded and included in further passage plan generation, including them in the expert knowledge base.

Future applications

What the future holds for the shipping industry is both uncertain and predictable. With the obvious boom for the container ship industry, a horrendous crisis emerged. For this reason, it yet not safe to draw any firm conclusions on what the market is to face. By contrast, based on research conducted in artificial intelligence studies on the one hand and in autonomous shipping on the other, it may be stated that an algorithm for unmanned, autonomous vessels is likely to be needed. This technological advance might render all ships currently managed directly by crew remotely controlled or even fully autonomous. With this trend proceeding, there is probably going to be a need for a suitable software that is capable of handling and managing a whole fleet of waterborne units (Kulbiej & Wołejsza, 2017). The human factor involved in this process remains significant as the most important part will still be the decisions on route details. In such a scenario, ship owners are likely to raise their income due to more optimal exploitation of vessels.

Conclusions

The artificial-intelligence-driven software promises to produce passage plans that are optimal under both qualitative and quantitative criteria. The algorithm itself is comprised of several smaller units, among which are decision support systems like NAVDEC.

Researchers' contributions to the topic of autonomous shipping are constantly increasing. Several projects are being conducted with an aim to introduce a vessel capable of solitary journeys without the compulsory aid of humans. Hence, the introduction of passage planning software based on algorithms similar to the one presented within this paper is all but inevitable.

Nonetheless, there is still a lack of practical tools that may be viable for planning intelligent ships' routes. Both alarming and providing the opportunity for a new generation of software, this phenomenon is undoubtedly proceeding in the direction as stated within the paper. Further future work of the authors will focus on the mathematical aspects of algorithms for route generation and prediction.

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