

AUTOMATIC SYSTEM FOR BATHYMETRICAL AUVS' NAVIGATION – BASIC CONCEPT¹

Autonomous Underwater Vehicles (AUVs) operate without any control of human operator. To ensure accurate navigation of such submersibles, not only the data gathered by navigational devices must be highly precise, but also special control algorithms must be applied to process these data. Those will be presented in this paper.

Keywords: *AUV, underwater navigation, control algorithms.*

1. AUTOMATIC NAVIGATION SYSTEM GENERAL DESCRIPTION

Autonomous underwater vehicle is a submersible, capable of navigating and undertaking pre-programmed tasks without direct control of the human operator, operating on 'deploy and forget' basis. This means that once launched into the water, it proceeds with a mission on its own without any direct or indirect control by human and completes its mission without human's contribution except for launching and recovering from the water.

To achieve that high level of autonomy, many problems must be solved. One of them is to ensure safe navigation of the vehicle so that it shall comply with at least following requirements:

- general:
 - not to collide with other objects AND,
 - not to leave operational area unless necessary AND,
 - proceed along route as short as possible to reduce power consumption AND,
 - not to submerge below maximum operational draught AND;
- specific mission requirements, for example:
 - not to fire explosives in vicinity of mother ship OR,
 - cover the entire survey area with sensors.

¹ The paper is a reprint of Chapter 2 of M.Sc. thesis titled: 'Conceptual design of a navigation system for an Autonomous Underwater Vehicle to be used in bathymetry surveys' by Krzysztof Wróbel, presented and defended at Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology, June 2013.

2. DEFINING THE MISSION

An AUV's mission can be defined as a set of tasks a vehicle must perform. Those tasks can be divided into blocks, each of them specifying tasks related to each other, enabling quick modifications of the mission's plan:

- a) navigation block – describes navigation tasks that state where the vehicle must proceed and forbidden areas – typical navigation plans are: path following, area exploration and measure tracking by means of maneuvering;
- b) measurement block – specifies measurement tasks regarding data provided by available sensors (configurable);
- c) communication block – contains communication protocols: sets of data to be transmitted, methods of communication (satellite, VHF etc.) limited by onboard communication equipment capabilities;
- d) logging block – indicates data logging tasks, in most cases saving sensor and navigational data, also referred to as a *black box*;
- e) supervision block – declares tasks to carry out in case of execution fault.

Every mission plan is made up of a task list, each task with name and unique identifier within the plan. Task specification contains the elements listed below:

- a) triggers list – specifies conditions to activate the task, basing on conditions met, time interval or exceptions – combined logically;
- b) actions list – specifies name and parameters of commands to execute while triggers are activated;
- c) inhibition period – inhibits trigger's state checking to ensure task execution is kept for at least a given time – even if triggers get immediately deactivated [3].

Task specification is based on logic programming. The biggest problem with this method is that for every task, block and mission, all possible circumstances must be addressed to avoid situation when a vehicle control system must improvise. Some solution to this problem can be in future offered by artificial neural networks, but their current development does not allow that to happen for at least few years to come.

3. INPUT DATA

Any moving object, including autonomous vehicles, may be considered as a system, influenced by numerous external forces, e.g. sea current. It performs previously defined tasks in presence of limitations, and effects of its work are evaluated using specified criteria [4].

AUVs must by definition operate automatically, which means that a control system for their movements must be designed properly. It is a difficult task which can be described in a simplified form as in Figure 1. Basically, some parameters must be adjusted, basing on present values of other ones, in presence of various disruptions as presented on Figure 2.

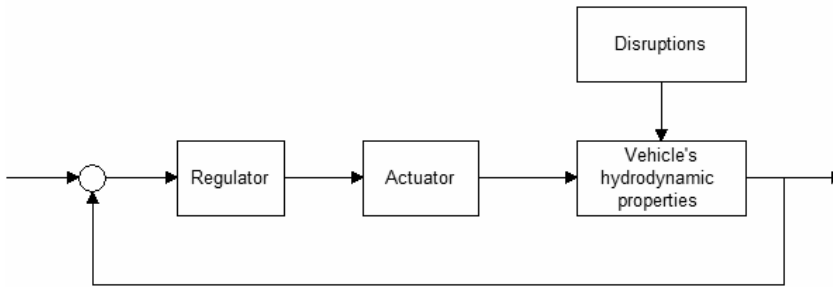


Fig. 1. Control system basic concept [4]

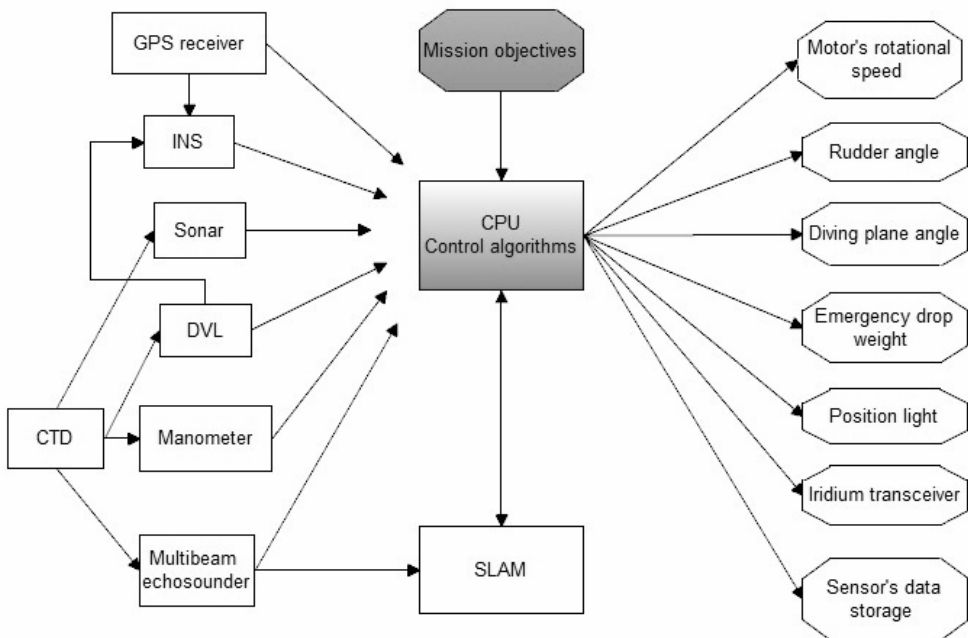


Fig. 2. Data flow diagram, Author's design

Input values of vehicle's control system include: desired course, present heading, pitch, 3D position, speed and data related to navigational situation around the vehicle: presence of obstructions or moving objects. The navigational parameters can be determined by using dedicated devices such as INS systems and forward looking sonars but also by extracting useful information from data gathered by sensors. This process is called data fusion and is particularly vital in SLAM method where data regarding landmarks can be delivered by multibeam echosounders.

In most of below stated algorithms, an optimization problem is being solved to ensure safe navigation of a vessel. To accomplish that, AUV control system must transform some data, collected by various devices into three-dimensional velocity vector, taking into account hydrodynamic characteristics of a vehicle itself.

4. DISRUPTIONS

AUVs operate in presence of numerous disruptions, influence of which must be included in control process. The most important of them are:

- ocean currents' speed and direction;
- sound speed changes.

Such parameters usually change together with the draught. Influence of ocean current on the vehicle can be included in vehicle's control system by the way it changes the AUV's course and speed in compare to normal circumstances. It is a normal practice in modern autopilots. However, it may be useful to specify conditions in which a current affects an AUV's actions in a way it cannot perform the mission any longer and the mission should be aborted or suspended.

While many navigational devices used by AUVs working principle is based on measuring the time of sound wave propagation in water, it may be found necessary to measure the speed of sound, especially during highly precise surveys. Speed of sound depends on hydrostatic pressure, salinity and temperature and is in range between 1400 and 1580 meters per second (up to 11% change). Those parameters change with draught and in some cases may be found highly non-linear, especially in areas where a seawater creates layers separated by thermocline and halocline for some reasons, like Baltic Sea. Speed of sound can be calculated by using Del Grosso method where previously specified parameters must be given - by devices called CTD probes (CTD stands for: conductivity, temperature, draught) or by SVP probes (sound velocity profiler).

5. CONTROL SYSTEM ALGORITHMS

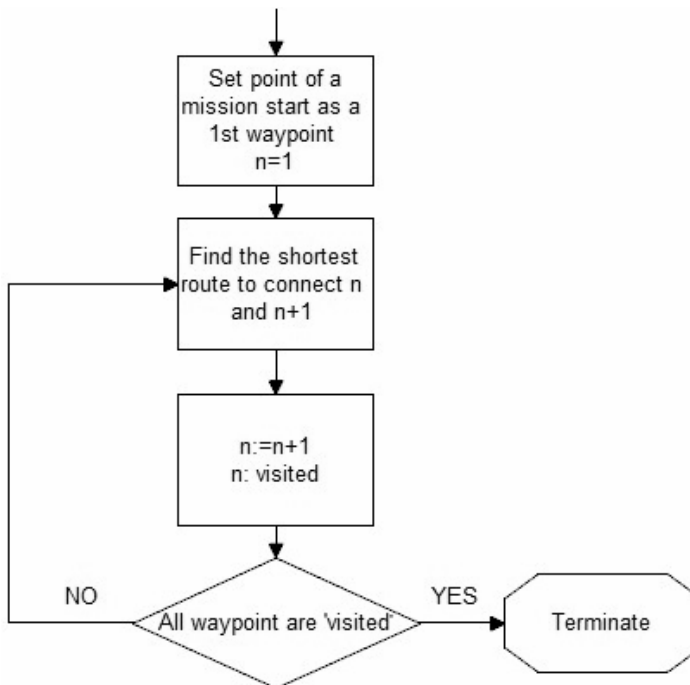
As the mission of underwater vehicle is defined, its movements must be planned, basing on available data regarding the area of operation. In next step, vehicle's control system's commands come into force, causing the submersible to move along the calculated path to the target. During the whole mission, differences between the way vehicle actually moves, and the way it should be moving, must be constantly calculated and minimized by correcting the resultant thrust.

Initially, the AUV is moving along a calculated route to reach the target – a single point in space where it is to perform its mission - or along a route planned in way that a whole area of survey is covered by the sensors. It is convenient that a route of a vehicle is programmed by human or calculated by vehicle's control system *a priori*. The route is planned without precise data regarding the area in which the mission will be performed. Then, if the conditions met in place are found unfavorable, the route can be slightly changed by the control system to avoid collisions etc. The process is similar to today's passage planning onboard merchant vessels - the voyage of a vessel is first planned on small scale maps

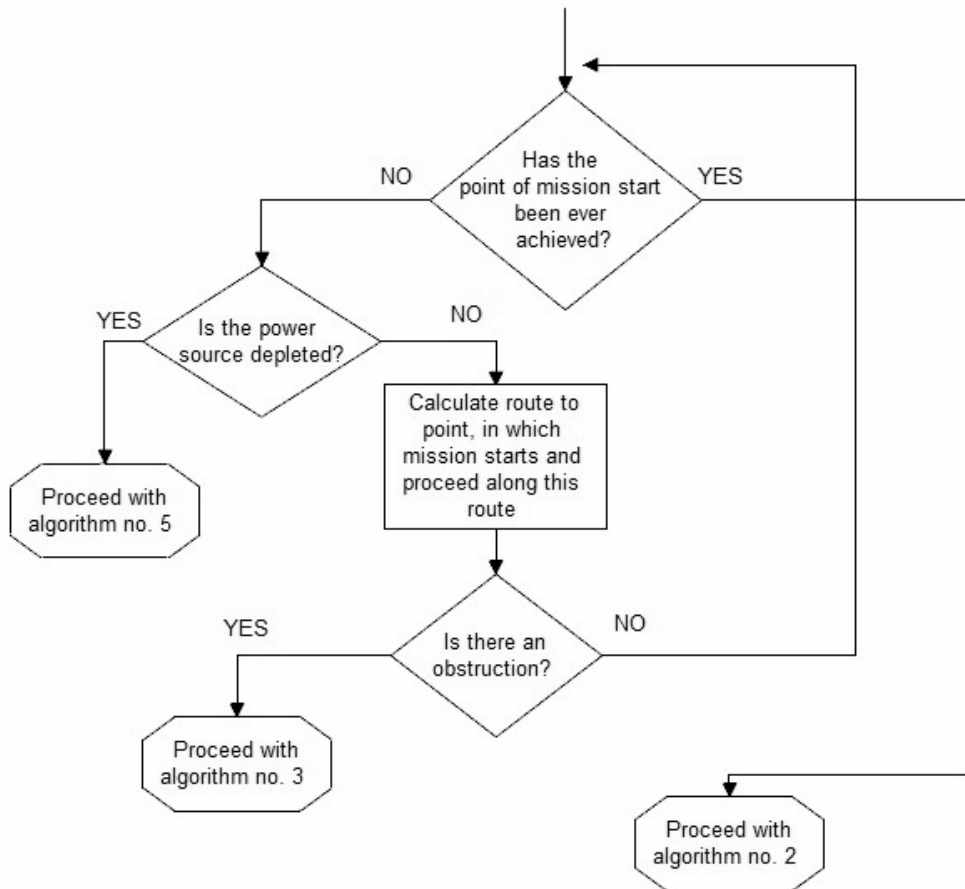
(routing charts), then on those of larger scale. Finally, navigator on the bridge alters the course of the vessel locally to avoid collisions or obstacles but after completing those maneuvers the vessel usually heads back to the original route smoothly.

A priori method of route calculation may be found unpractical as there must be an employee to actually set it. Another approach to route calculating is that the vehicle's control system solves the modified 'traveling salesman problem' (returning to point of origin acceptable, but not necessary). Here, the system must possess only the data regarding survey area boundaries and sensors' swath width. It then discretizes the area to set a grid of waypoints in a way that a whole area's seabed can be covered by sensors with sufficient resolution. In a next step, a 'nearest neighbor algorithm' (NN) comes into force, determining the route a vehicle should choose in order to perform its task with highest efficiency [1]. The NN algorithm is a tool to determine the shortest route linking all the waypoints by comparing sum of distances between n^{th} and $n+1^{\text{th}}$ waypoint. Consecutive iterations are the effect of selecting different waypoints as point of start (*NN Algorithm*).

NN Algorithm: establishing route to connect all pre-determined way points

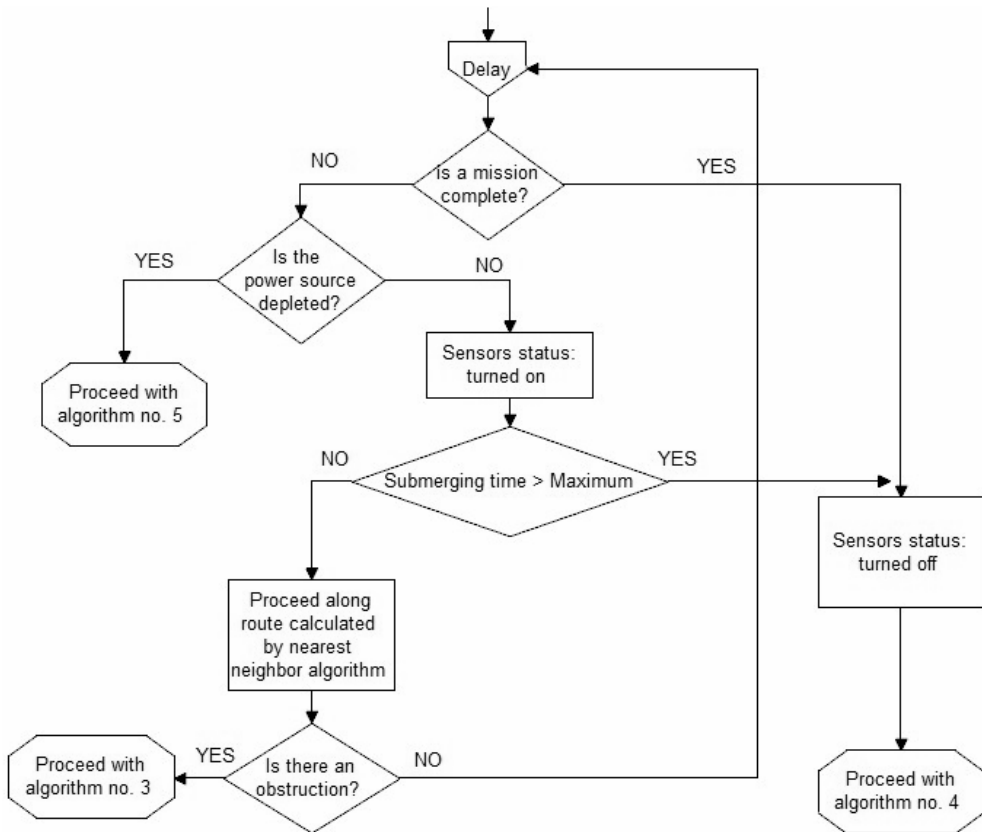


Algorithm no. 1: voyage planning from surface position to the place where actual works start:



NN Algorithm only defines vehicle's route inside the survey area. To achieve the first waypoint, AUV's control system must calculate the route from its present position to it. From navigational point of view, mission of AUV as a whole can be divided into several stages in which one of following algorithms is performed.

Algorithm no. 2: performing mission:



If the power supply falls below pre-determined margin of safety, say 7–10% of total capacity excluding emergency power source, vehicle's mission ought to be aborted. Switching into *Algorithm no. 3*. is triggered by specific signal transmitted by forward looking sonar module.

Bathymetry surveys are relatively simple missions that consist of proceeding along calculated route in a specified distance from the seabed with sensors switched on and set into the proper operational mode. Vehicle proceeds from one waypoint to another, but estimating the position may result in never actually achieving the waypoint itself (condition when position of vehicle is equal to waypoint's position). The distance, passing in which will mark a waypoint as 'achieved' shall be determined by human operator and depends on precision of navigation, especially control of rudders and propellers.

Delay included in above loop is to ensure that control system is able to process data from devices and sensors and execute the commands before another set of data is received. Such delay cannot be too big, otherwise some changes in the environment may remain unnoticed. Maximum submerging time check is to ensure that GPS (RTK) fix is obtained from time to time to increase position precision.

Whenever sonar indicates presence of an obstruction (Figure 3) ahead of the vehicle, *Algorithm no. 3* comes into force. In order to by-pass the obstruction, a new waypoint shall be set in a distance equal to present sonar's range in a sector where no object has been detected. As far as it is possible, the waypoint should be at the same draught of water on the vehicle's starboard side. Research indicates that avoiding the obstruction by changing draught is 20% less power-effective than by changing the course. It means that as long as it is possible, an AUV should be trying to pass by an obstacle without changing an operational draught [6].

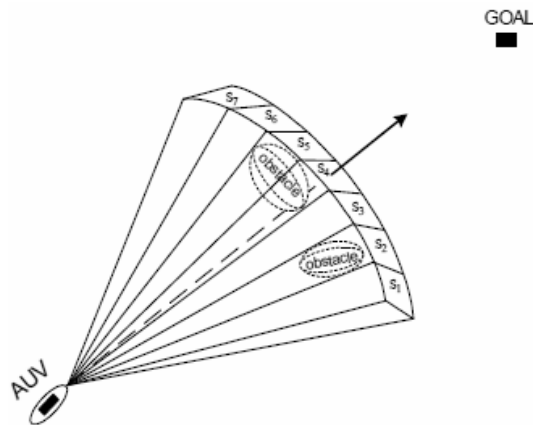


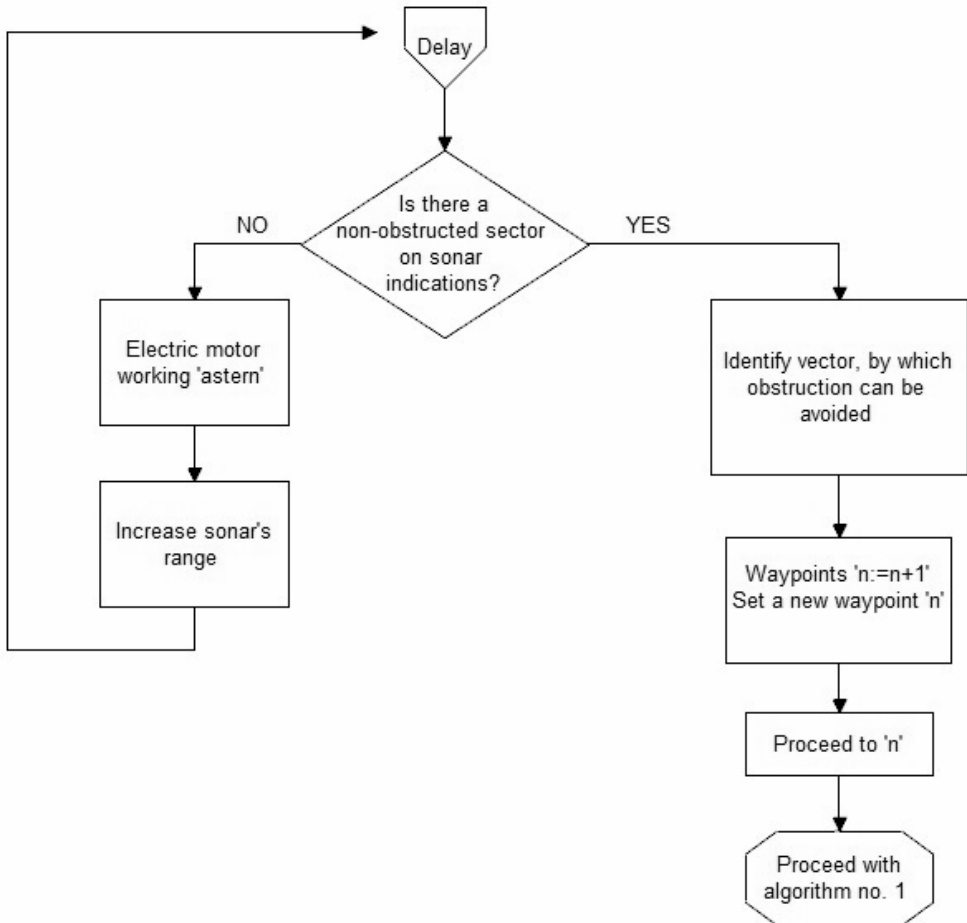
Fig. 3. A model of forward looking obstacle avoidance sonar [6]

Waypoint shall also be established leaving safe distance to obstructions so that the vehicle will not collide with them due to ocean current disruptions, rudder control inaccuracies etc. To prevent such events, tactical diameter of vehicle's circulation shall be considered together with other characteristics of its maneuverability.

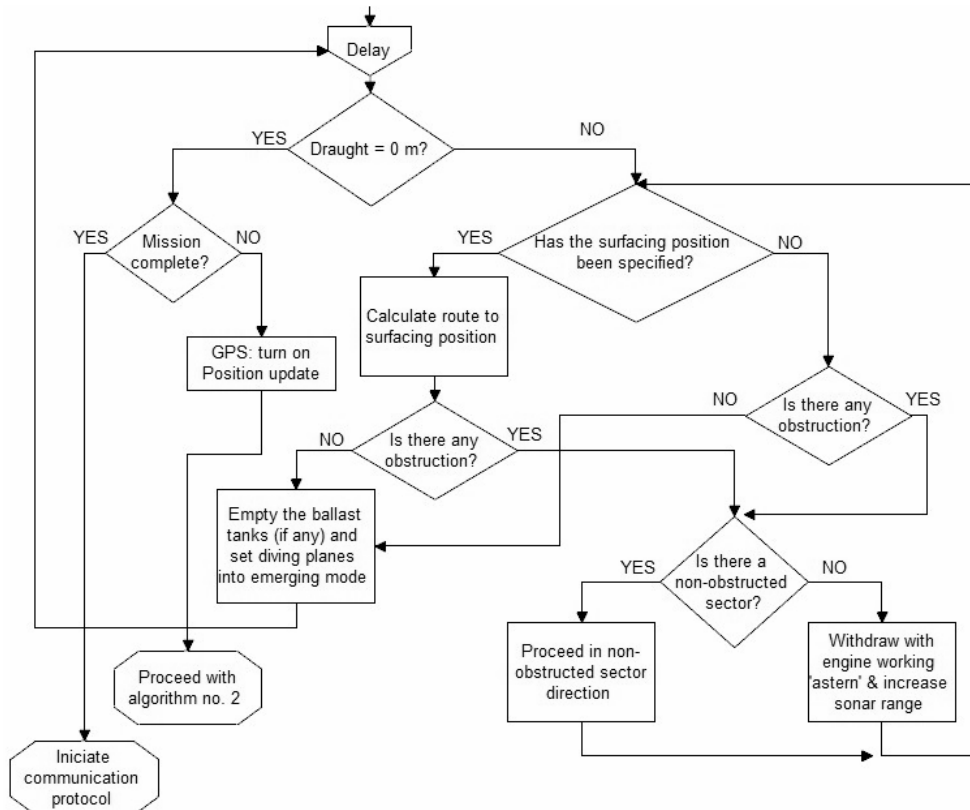
If the obstruction is found to be moving, its relative velocity vector is to be calculated together with CPA and vehicle's course is to be altered. There is also the possibility that obstruction could not be avoided. In such case, vehicle shall withdraw with its engines working astern and increase the sonar's range looking for possible passage. Eventually, the distance to the obstruction will increase in a way that it could be avoided.

During collision-avoidance maneuvers, emergency resurfacing algorithm should remain inactive. That is because forward looking sonar indicates presence of obstruction which shape is not entirely known and initiating emergency surfacing in vicinity of it could cause damage by hitting objects located above the vehicle. In worst case scenario, if an AUV does not reach free space before the power source is depleted, letting go an emergency drop weight by a dead-man's switch will cause emerging of the vehicle that was already deemed to be lost.

Algorithm no. 3: navigating in vicinity of dangers and hazards:



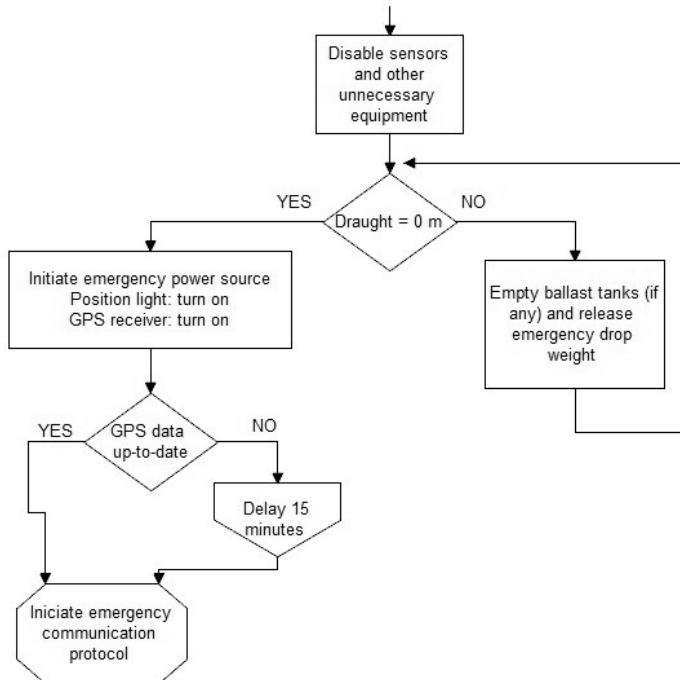
Algorithm no. 4 is a loop that shall eventually lead to safe surfacing of the vehicle and picking it up by support vessel. If a position of surfacing has been specified, vehicle should find itself in this point covering as much distance as possible underwater as it is designed to deal with such environment. During surfacing procedure, special attention should be paid to collision avoidance not to collide with support vessel which is likely to navigate in vicinity of bathymetry survey area. Finally, after reaching the sea surface vehicle is to initiate communication protocol and transmit its position and readiness to be retrieved.

Algorithm no. 4: resurfacing:

If the mission is not complete and the GPS fix has been obtained, AUV will submerge again and carry on with its mission. Except for mission completion, *Algorithm no. 4* shall also be initiated whenever sensors' malfunction is detected or other unfavorable conditions appear.

Whenever power supply happens to fall below the safety margin specified by vehicle's manufacturer or operator, or other unexpected events such as rapid decrease of position precision occur, an emergency surfacing algorithm causes the vehicle to resurface. This does not apply to a situation when power source is completely down and letting go an emergency drop weight forces the surfacing. In *Algorithm no. 5*, all unnecessary equipment is turned off during the operation. The assumption is that for some reason the AUV became unable to navigate and its position is unreliable. Thus, a GPS fix must be obtained which can take up to 15 minutes if the ephemeris have expired.

Algorithm no. 5: emergency resurfacing:



6. OUTPUT DATA

The concept of automatic navigation of an autonomous underwater vehicle is based on adjusting the thrust parameters to the conditions met deep below the sea surface in order to complete the vehicle's mission. To achieve this, following parameters must be constantly controlled: propellers' rotational speed, rudder angle, diving plane angle. For the AUVs, the most commonly used system is with one propeller, rudder and a diving plane. This configuration is sufficient for most of AUVs' applications.

Regulation of underwater vehicle's speed can be performed by changing the rotational speed of the propeller, and this in turn is based on variable number of electric motor's revolutions per minute. As an output of the control's system, a number of those rotations is given instead of a longitudinal speed. This must be calculated basing on a distance to the target, limitations in time of operation and hydrodynamic properties of the vehicle:

$$m \cdot \dot{v} = T \cdot (1 - t) - T_R$$

Where:

- m – vehicle's weight,
- v – vehicle's velocity,

- T – thrust, dependant on propeller's rotational speed ω_p ,
 T_R – resistance to motion, dependant on m and v ,
 t – propeller's suction coefficient [2].

By identifying vehicle's hull resistance to motion and $T = f(\omega_p)$ characteristics, velocity can be controlled precisely. On the other hand, during the bathymetry surveys precise control of velocity is not crucial and can be replaced by precise measuring of the speed itself.

Precise control of heading and pitch is more important. It defines the direction in which the vehicle will proceed and by that its future position. For heading and pitch control, proportional-integral-derivative regulators are used as described by equation below [4]:

$$\alpha_z(t) = K_p \cdot \left[\Delta\Psi(t) + \frac{1}{T_i} \cdot \int \Delta\Psi(t)dt + T_d \cdot \frac{d[\Delta\Psi(t)]}{dt} \right]$$

Where:

- α_z – rudder angle,
 $\Delta\Psi$ – difference between actual and desired heading,
 K_p – gain,
 T_i – controller integral time,
 T_d – derivative time.

Similar equation is solved to obtain desired pitch. Rudder and diving plane angles depend on the difference between present heading/pitch and the direction to the nearest waypoint. PID controllers ensure smooth regulation of discussed values and do not allow a situation when vehicle's resistance to motion increases significantly due to big rudder and diving plane angles. Gain can be adjusted by system's designer or by artificial neural network.

7. SAFETY AND RELIABILITY

The major problem with AUVs is that in almost every moment, a fatal error can occur and the vehicle can find itself no longer capable of navigating. In other words, it will be lost forever in a deep sea, its mission not completed and gathered data – never to be recovered. Described problem occurs in a situation when the vehicle meets conditions it cannot adapt to for any reason.

In a worst-case scenario, if a vehicle finds itself no longer capable of navigating, an emergency surfacing algorithm is activated. Even if it does not work, an AUV normally has a positive buoyancy which is additionally improved by an emergency drop weight, let go in no-voltage conditions. Therefore, a loss of power supply must eventually occur and a vehicle shall resurface either way. Then the only consideration for the AUV is to initiate emergency communication protocol sending own position and waiting to be recovered.

CONCLUSIONS

A navigation control system of Autonomous Underwater Vehicle has been preliminarily designed to ensure that vehicle's mission is performed safely and efficiently. In fact, the actual design of such system is a result of scientists, programmers and engineers cooperation and is a very difficult task as many various factors must be taken into consideration.

REFERENCES

1. Cates J.R., *Route optimization under uncertainty for unmanned underwater vehicles – MSc. thesis*, MA: Massachusetts Institute of Technology, Cambridge 2011.
2. Domachowski Z., Ghaemi M.H., *Okrętowe układy automatyki*, Wydawnictwo Politechniki Gdańskiej, Gdańsk 2007.
3. Fernández-Perdomo E., Cabrera-Gámez J., Domínguez-Brito A.C., Hernández-Sosa D., *Mission Specification in Underwater Robotics, X Workshop de Agentes Físicos*, Cáceres 2009.
4. Lisowski J., *Statek jako obiekt sterowania automatycznego*, Wydawnictwo Morskie, Gdańsk 1981.
5. Rowiński L., *Pojazdy głębinowe – budowa i wyposażenie*, Wydawnictwo WiB, Gdańsk 2008.
6. Seong-Gon K., Yong-Gi K., *An Autonomous Navigation System for Unmanned Underwater Vehicle*, InTech, Rijeka 2009.

KONCEPCJA SYSTEMU AUTOMATYCZNEJ NAWIGACJI AUTONOMICZNEGO POJAZDU PODWODNEGO DO ZADAŃ BATYMETRYCZNYCH

Streszczenie

Autonomiczne pojazdy podwodne operują w toni wodnej bez jakiegokolwiek ingerencji operatora. Aby nawigacja takich pojazdów była dokładna, nie tylko dane zebrane przez ich urządzenia nawigacyjne muszą być bardzo precyzyjne – trzeba także zastosować specjalne algorytmy sterowania i obróbki danych. Podstawową koncepcję takich algorytmów zaprezentowano w niniejszym artykule.

Słowa kluczowe: *pojazdy podwodne, nawigacja, sterowanie.*