Buoyancy Control of a Semiautonomous Underwater Vehicle for Environmental Monitoring in Baltic Sea

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***Abstract* – This paper describes a preliminary prototype of a semiautonomous underwater vehicle. The vehicle is designed for environmental inspection in a Baltic Sea region. The environmental characteristics and the purpose of the vehicle set several restrictions to the vehicle's design. The concept represented here aims at meeting these restrictions. The paper focuses on describing a novel buoyancy control mechanism based on two controllable lateral ballast tanks. The buoyancy control permits using the vehicle in two modes - horizontally compressed and vertically compressed. These modes are used in different environmental conditions and for different monitoring tasks.**

I. INTRODUCTION

Our goal is to design a vehicle for environmental monitoring in Baltic Sea that is in the first place meant for monitoring of underwater vegetation and benthic morphology.

Baltic Sea is one of the most severely polluted seas in the world. The extent and distribution of underwater vegetation gives a lot of information about pollution, climatic conditions, ice conditions etc., therefore vegetation is monitored regularly. At present underwater monitoring is done by divers, which is laborious, expensive and dangerous.

We have designed a prototype of a vehicle that is equipped with an underwater camera and is meant to replace the human diver. In addition to hydrobiological surveys the vehicle can also be used to record other environmental parameters like water temperature, pH-level, salt content, etc. Since the device is equipped with an underwater camera it can also be used for underwater inspection e.g. at rescue operations, construction work, etc. in shallow waters.

The paper at hand describes the preliminary prototype of the vehicle and focuses on a novel buoyancy control mechanism. The buoyancy control permits using the vehicle at different orientations, either horizontally or vertically compressed, depending on the environmental conditions and the task specification.

This paper is organized as follows. In the rest of the introductory part we describe the task requirements. Next, we describe our buoyancy control mechanism. Sections 3, 4 and 5 describe the mechanical, pneumatic and control system of the prototype respectively. We finish this paper with concluding remarks and an outline for the future work.

A. Task description

The requirements determining our vehicle's design can be divided into two large categories. The first category consists of environmental factors that are unique to the Baltic Sea. The second category is the human and task specific factors. In the following subsections we describe both of the categories closer.

B. Environmental factors

Baltic Sea is different in several senses from subtropical and tropical seas or exposed seas like Nordic Sea. The factors influencing our choices for the vehicle's design are the following:

1) Depth: Baltic Sea is relatively shallow and therefore the underwater vehicles do not have to operate under high pressure.

2) Turbidity: water is very turbid due to floating detritus and therefore visibility is very low.

3) Extension of vegetation: due to low visibility, the euphotic zone (the zone of penetration of light into the water column) is rather narrow and therefore the vegetation is limited to the costal regions in the depth down to approximately 20m. The regions of interest for environmental monitoring are usually near the coastline in the depth from 1m to 6m.

4) Properties of the seabed: most of the seabed in the depth of interest is covered with mud or small particles of zoo- and phytoplankton that has settled down and is extremely volatile.

5) Human inhabitancy: Baltic Sea is under a severe anthrophic pressure. Costal regions that are especially interesting for monitoring are full of harbours, beaches, fishing nets, dense surface traffic, etc.

C. Human- and task specific factors

This research is strongly demand-driven and therefore we pay lot of attention to satisfying the requirements of the users, which are in the first place environmental scientists. The human and task specific factors that influence our vehicle's design are the following:

1) The main function: the main function of the device is to facilitate environmental monitoring. The highest priority is to facilitate monitoring of underwater vegetation.

2) Additional functions: if possible, the device should also permit measuring other environmental parameters, like temperature, pressure, salt content and make it possible to correlate these parameters with hydrobiological data. It could also be used for other type of benthic surveys and diving under ice in winter.

3) Operational requirements: the device should be portable, preferably operated by one person only; it should support storing, processing and mapping of environmental data.

4) Cost requirements: since the vehicles can occasionally be lost, their cost has to be kept as low as possible.

II. DESIGN CONCEPT

Categorization provided in [1] divides underwater vehicles according to their purpose into three categories. The first category is commercial vehicles used mainly by offshore oil and gas industry for exploitation and exploration of oil and gas fields. These vehicles are usually heavy, they tolerate high pressure that makes them applicable in deep ocean surveys and they are very expensive. Military vehicles are basically used for reconnaissance, intelligence gathering and demining, they often operate in a fleet, are fully autonomous and expensive.

The third category is low cost academic research tools, like for example [2]. The vehicle described in this paper certainly falls into the last category. Its main function is to support scientific benthic surveys. Also its cost has to be kept low to afford using several vehicles along the costal line and to decrease the risk of loosing some of them in fishing nets or on underwater rocks.

According to the restrictions specified above we describe the main features of the design.

A. Semiautonomous and remotely operated modes

Underwater navigation and mapping is still a field of intensive research. Despite of several emerging solution, the methods of underwater navigation are still under development [3]. In addition, a fully autonomous vehicle must carry its own batteries. The batteries have to be charged often and they increase the weight of the vehicle. A fully autonomous vehicle is more likely to be lost (environmental researchers report every year loss of theft of a great deal their equipment). Considering these disadvantages we propose a semiautonomous vehicle that can be operated in two different modes:

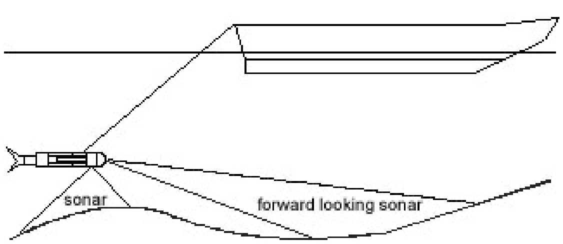

Fig. 1. Using the vehicle in the towing mode.

1) Towing mode: in this mode the vehicle is towed behind a boat or a ship (see Fig. 1). With the help of the bow sonar it adjusts its height from the bottom. The power supply and localization unit are on the surface as well as the data storage for the gathered data. The towing mode permits covering large distances at speed. At present, benthic surveys are often done by towing a diver behind a boat. According to preliminary calculations, replacing the diver with a vehicle like this will be approximately 10 times more efficient.

2) Remote control mode: the operator can manually drive the vehicle. This mode requires more control surfaces for greater manoeuvrability. This mode can be used for closer inspection of underwater sites or diving under ice.

B. Fin-like control surfaces

Underwater vehicles almost exclusively use thrusters for locomotion. This is an effective means of propulsion but as a side-effect it generates high turbulence. The bottom of Baltic Sea is to a great extent covered with very lightweight detritus, specially the regions of the greatest interest for environmental monitoring. Tests with underwater vehicles show that at the moment the thrusters are switched on, visibility becomes practically zero and it takes a long time before the extremely volatile detritus settles down again. We therefore have decided to use elevators instead of the thrusters in a towing mode to control the depth of the vehicle and additional rudders for yaw stability.

In the future, we aim at using the caudal-fin like propulsion in the remotely controlled mode and pectoral-fin like motion for stability and manoeuvrability [4][5], but this is still a topic for future research.

C. Orientation of the vehicle

The novel aspect of this vehicle is a flattened streamlined body that can be used at different orientations, either horizontally or vertically compressed (Fig. 2).

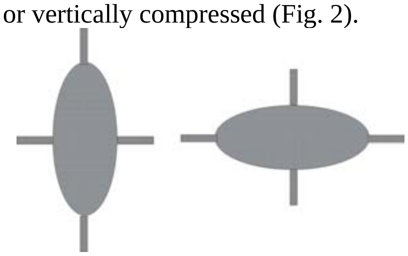

Fig. 2. Orientation of the vehicle: vertically compressed (to the left) and horizontally compressed (to the right).

The two orientations are used in different conditions.

1) Horizontally compressed. This orientation will be mostly used in the towing mode. The advantage of the horizontally compressed shape is that the whole body of the vehicle operates as an elevator and works against lift forces. Horizontally flattened body can also be used to submerge to the seabed for a closer inspection. Since its cross section is smaller than of the vertically compressed body, it is easier to stabilize the vehicle in lateral currents.

1) Vertically compressed. This orientation will be mostly used in the remote controlled mode and in a towing mode at low speeds in very shallow waters with opulent vegetation. Costal regions interesting for hydrobiologists and other environmental scientists are often shallow bays fully covered with underwater vegetation. Some algae can grow up to 1m – 1.5m and reach up to the water surface. A vehicle with a vertically compressed body is much less likely to get stuck in the dense vegetation or between underwater rocks. A laterally compressed vehicle is able to heave and submerge faster at low speeds and has better manoeuvrability. When a caudal fin is added, it can be used to propel the body forward in a remotely operated mode.

The usage of two orientation modes is supported by biological evidence. Dorsoventrally compressed fishes (like rays and stakes) are ground-dwelling fishes. Their body shape is adapted to bottom following. Laterally compressed body shape (like of sunfish, bluegill and angelfish) is good for leisurely swimming and hiding or for predators who need stability for attack and manoeuvrability.

III. BUOYANCY CONTROL

Underwater vehicles use buoyancy control mainly to submerge and surface or compensate for a changing weight For example, [6] uses a variable buoyancy control to compensate the weight of the payload fetched from the bottom. While buoyancy is traditionally controlled by compressed air and water, alternative methods have also been reported. For example, buoyancy control of [7] is inspired by sperm whales and uses oil temperature regulation for decent and ascent.

The novel aspect of this research is that it uses buoyancy regulation not only to compensate its negative buoyancy and for depth control but also to change the orientation of the vehicle.

The general idea is to use two ballast tanks at both sides of a compressed streamlined body (Fig. 3). In the horizontally compressed mode both tanks are used to regulate buoyancy. In the vertically compressed mode, only the upper tank is filled with the air and is used to control vehicles buoyancy.

When the vehicle has zero buoyancy then its density is equal to the density of sea-water. The density of the vehicle depends on its mass and volume. Since the vehicle will be constantly rebuilt as the tests proceed and requirements change, buoyancy of the vehicle can calculated only approximately. Even when the prototype is built ready, its buoyancy still depends on the sensors added or removed, the content of the water containers and the salt content of sea-water as well as on the density of air left in the compressed air balloon. Therefore the buoyancy is fine-tuned with the help of the trimming weights.

Vehicle's buoyancy is designed to be negative. To have zero buoyancy the air balloons are initially filled with 0.5 litres of air. The estimated overall weight of the vehicle is approximately 15 kg. The compressed air balloon can hold 64 litres of air and both air expansion chambers can contain up to 1.5 litres of air. That means that total lift force can be approximately 2.5 kg and for changing orientation we have about 1 kg directional lift force available.

IV. MECHANICAL STRUCTURE

The layout of the interior of the vehicle is represented in Fig. 4. Since our aim is to keep the cost of the vehicle low, the prototype is built from off-the shelf components that are easily replaceable.

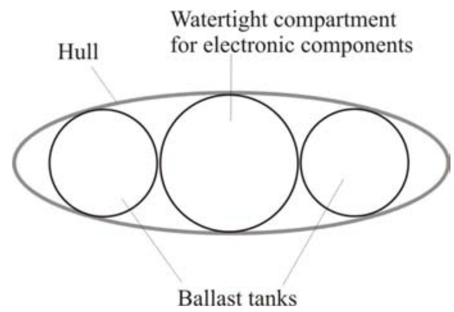

Fig. 3. The design concept of the orientation changing buoyancy control.

The streamlined hull of the vehicle houses the pneumatic system, servos and stepper motors to control the control surfaces, electronic circuits, batteries and sensors. The supporting rod of the vehicle is used to fix these components. The hull is floodable and made of fibreglass. Openings in the hull are for cameras, forward and bottom-looking sonar, lights, and to attach the rudders to the body of the vehicle.
Variable ballast tanks are placed at both sides of the vehicle and made of PVC tubes. Trimming weights can be added or removed from the bow and stern ends of these tubes to compensate changes in buoyancy when modules are changed or payload is added.
The compressed air balloon is fixed between the supporting rods between the ballast tanks at the centre of the vehicle.
The PVC tube in the bow part of the vehicle is a watertight compartment sealed with a silicon sealant and fixed between the supporting skeleton. This compartment houses control electronics and batteries for emergency cases. When the off-board power supply is disconnected or communication with the surface control unit is lost, the vehicle will surface.
The watertight PVC tube housing in stern of the vehicle is for a stepper-motor powering the caudal fin.

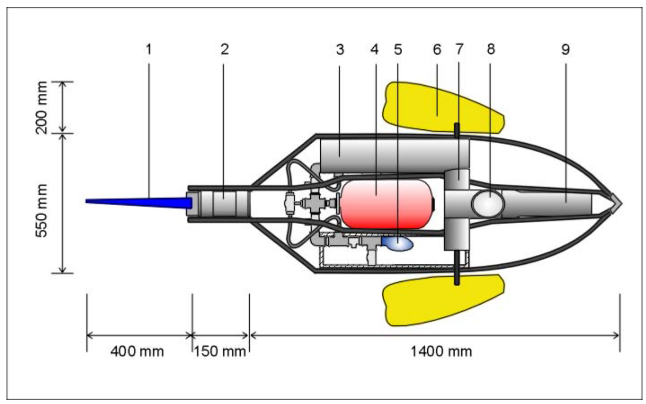

Fig. 4. Internal layout of the vehicle
(1-fin, 2-stepper, 3-PVC tube, 4-compressed air tank, 5-rubber tank, 6-fin, 7-stepper, 8-camera, 9-batteries and electronics)

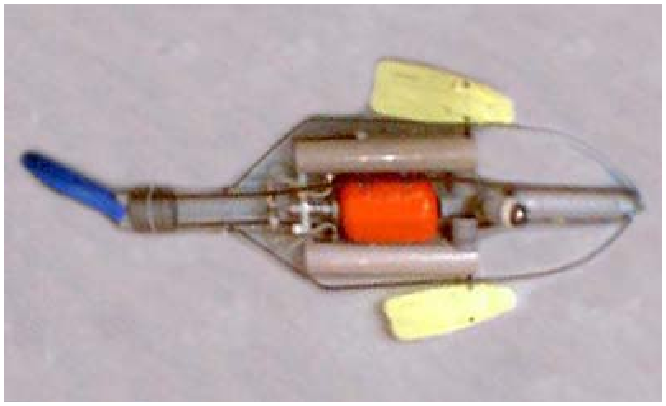

Fig. 5. Partially completed prototype of the vehicle without the floodable outer shell.

The void between the PVC tubes and the compressed air balloon coincides with the opening in the hull and is meant for a down-looking camera and sonar. There is a symmetrical opening on the upper part of the hull that permits adding an additional camera. When the vehicle is operated in a vertically compressed configuration, aquatic environment can be inspected at both sides of the vehicle. The void in the bow in front of the watertight compartment is prepared to host the bow sonar.
The empty regions at both sides of the watertight compartment are prepared for containers of water samples and sensors that analyse them (like salinometer, microscope, PH- sensor, etc.). It is planned that these sensors are interchangeable and are used depending on the environmental conditions and the mission.
The partially completed prototype is represented in Fig. 5. The voids on both sides at the bow will be completed with water containers and sensors to analyse water samples.

Fig. 6. LED light source with housing.

As it was explained in introduction, water in Baltic Sea is quite turbid and therefore visibility is low. Two halogen lamps in front of the elevators are used to increase visibility or to cancel out reflections when the vehicle operates in very shallow water in a direct sunlight. The reason of having two sources of light on the sides of the vehicle is that there is usually lots of floating plankton and parts of underwater macrovegetation. Since camera is attached in the middle of the vehicle, the scene is illuminated from the sides and reflection is not as intensive as in case of a single source of light. In addition to the halogen lights, to arrays of LEDs are used for spectral analysis of vegetation (see Fig. 6 and Fig. 7).

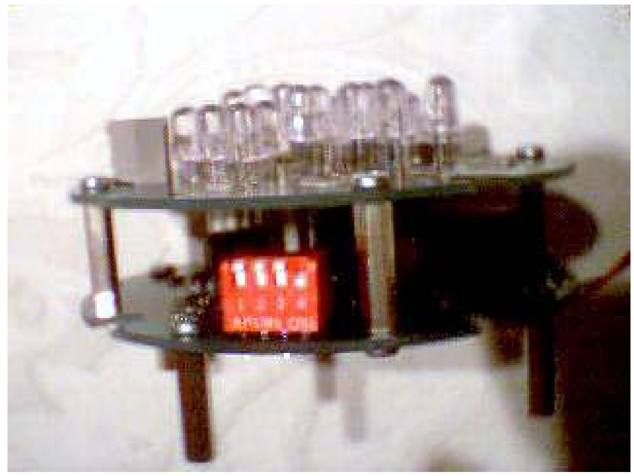

Fig. 7. LEDs and control electronics.

V. PNEUMATIC SYSTEM OVERVIEW

Buoyancy of the vehicle is controlled by regulating the volume ratio of water and air in ballast tanks. The tanks have outlets at both ends so that water can flow in or out. In the middle of the tank, there is an air expansion chamber made from rubber. When the chamber is filled with air, water will drain from the tank and the buoyancy of the vehicle increases.
Both ends of the ballast tanks have also a place for trimming weights that can be used to compensate for the change of weight of the vehicle or adjust the centre of gravity when modules are changed or added.
The compressed air balloon supplies air at a pressure of approximately 8 at. This air is used to inflate the air expansion chambers in the ballast tanks (Fig. 8). The compressed air balloon is connected to the chambers with air inlet hoses. A Y-branch divides the inlet path to two branches. There are two pairs of valves at both branches. The first pair of valves is outlet valves that can be controlled independently. This permits inflating or deflating only one of the air expansion chambers at time when the vehicle is operating in a laterally compressed configuration. The second pair of valves is the check valves that prevent water from intruding into the pneumatic system.
The air outlet hoses are attached between the air expansion chambers and openings at the frontal part of the vehicle. Like inlet paths, the outlet paths have check and outlet valves.
Both branches are connected together with additional Y-branches, a hose and an outlet valve near the frontal end of the pressured air balloon. This valve is opened when the vehicle is operating in a horizontally compressed

configuration. This guarantees an equal pressure in both air expansion chambers and therefore improves pitch stability and controllability of the vehicle.

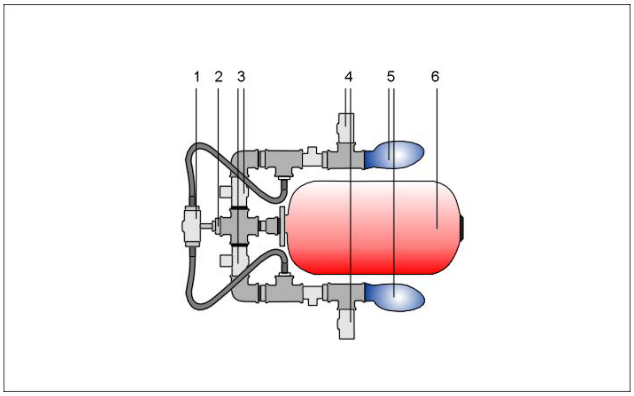

Fig. 8. Pneumatics
(1-pressure equalizing valve, 2-air inlet, 3-input valves, 4-output valves, 5- rubber tanks, 6-compressed air tank)

VI. CONTROL

The block diagram of the vehicle's electronics is provided in Fig. 9.

The control of the vehicle is hierarchical. The surface control unit is a laptop computer connected to the GPS receiver and accessible for a human operator via a graphical user interface. The surface unit receives and stores sensor data that can be later analysed by environmental scientists. It also receives acknowledgement and state signals from the underwater unit and sends down high level commands.

The surface and underwater control units are connected via an Ethernet link. The underwater control system is in turn hierarchical, consisting of a Strong ARM 400 MHz processor on the highest level, TI MSP processor on the middle layer and PIC processors on the lowest layer.

The X-Scale architecture based Intel Strong ARM processor is responsible for communication with the surface unit, for passing up camera data, for processing the received high level commands, high level planning and controlling the next control level.

It is connected to external data storage and colour camera via an USB link and to the compass and inclinometer via RS232. Connection to the lower level MSP processor is also established through RS232 serial interface.

Texas Instrument's MSP430 microcontroller is an ultra-low power 16-bit RISC mixed-signal processor. It receives high level commands from Strong ARM, decomposes the tasks and passes commands down to the next level microprocessors responsible for executing the commands. It also reports back to the Strong ARM processor about the success or failure of the commands.

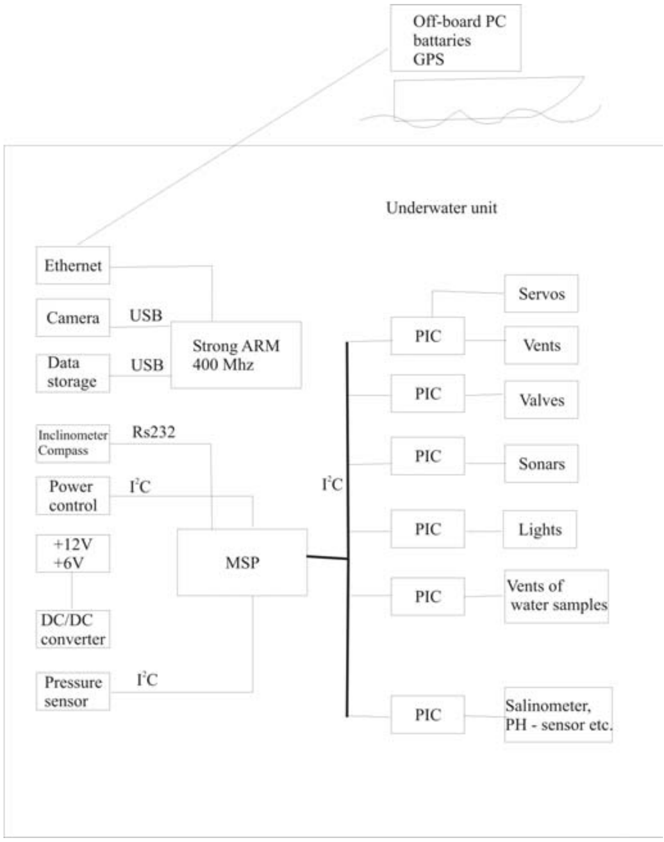

Fig.9. Block diagram of electronics and control.

The lowest level of control consists of an array of Microchips' PIC18F1320 16-bit 40 MHz processors. These processors are responsible for steering the actuators and receiving sensor data. They are connected to the MSP processor via I^2C interface.

The first PIC processor is responsible for driving the motors of the rudders and vents. The next processor drives the valves of the pneumatic system. The third processor receives data from the bottom and front-looking sonar, analysis the data and passes it forward to the MSP processor.

The fourth PIC processor is used to establish proper lightning conditions. Our preliminary experiments have shown that spectral analysis would facilitate recognition and categorization of underwater macrovegetation. First, it could help a human expert to distinguish between plants and uncovered seabed in case of low visibility. Second, we aim at developing an image processing method that automatically recognizes vegetation from a video tape. We have therefore built an array of LEDs with different wavelengths (Fig. 7). The PIC processor under consideration is thus responsible for steering the arrays of LEDs and switching the halogen lamps in and out when spectral analysis is performed.

The next PIC processor steers the vents of the containers of water samples.

Additional processors can be added to process data from additional sensors.

VII. CONCLUSIONS AND FUTURE WORK

This paper describes the preliminary prototype of an underwater vehicle. The vehicle is built for environmental inspection in shallow waters of Baltic Sea. The design concept is based on the environmental restrictions, human factors and cost requirements.

The novel aspect of the vehicle's design is the buoyancy control that permits using the vehicle in two orientations, horizontally and vertically compressed. The orientation can be changed by controlling ballast tanks at both sides of the vehicle.

At present, the construction of the vehicle is mostly complete but underwater test are not yet done. The next phase of this study is therefore a careful testing of the system and all subsystems of the vehicle both is pool environment and in a natural environment where currents and surging is present, and the bottom is uneven.

This semiautonomous vehicle is designed to be used in two modes, a towing mode behind a boat and in a remotely operated mode. The towing mode permits covering long distances at high speed compared to the human diver and therefore considerably increases the efficiency of environmental inspection. We also anticipate that the towing mode is easier to implement that the remotely operated mode since the vehicle has less degrees of freedom and needs fewer control surfaces.

We therefore first aim at building a working prototype that can be used in the towing mode by environmental scientists. This involves in fist hand implementation of depth control of the vehicle with help of rudders and front and bottom looking sonar at the same time maintaining yaw and roll stability. At present, the preliminary control model is ready but not tested yet.

The remotely operated mode in a laterally compressed orientation is a more complex task and definitely implies thorough investigation of control models and vehicle's kinematics and dynamics.

Parallel to the vehicle's design we also work at image recognition algorithms for classification of underwater vegetation.

V. ACKNOWLEDGEMENT

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