DESIGN, CONTROL AND APPLICATIONS OF THE UNDERWATER ROBOT ISFAR

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Abstract:

This paper describes the design of the underwater robot Isfar which belongs both to a miniROV and AUV classes vehicle. The mechanical structure, the architecture of the control system and the most significant applications of such vehicle are presented together with the classification of the Isfar within particular classes of underwater vehicles.

Keywords: *unmanned underwater vehicle, mini remotely operated vehicle, autonomous underwater vehicle, underwater robot.*

1. Introduction

The vehicle constructed by a Serbian inventor and engineer Nikola Tesla, considered as the first UUV (Unmanned Underwater Vehicle), was presented on annual exhibition of electrical engineering in 1889 [10],[11]. Yet, rapid development of such vehicles came out on late, on 50s of 20th century, when vehicles CURV (Cable-controlled Underwater Re-search Vehicle) and TONGS (Television Observed Nautical Grappling System) were introduced [12].

The main goal of such vessels was to operate in high depths, that are beyond the divers' reach.

There was a trend to build vehicles that were capable of exploring oceanic depths up to several thousands of meters.

Contemporary engineers does not focus only on exploration of high depths, but also on granting security of divers making their duties or on environmental surveillance. Small underwater units became now more significant. Engineers and scientists design them to manually operate in shallow waters and littoral zones [9].

The commercialisation of specialized, low-cost, mechanical and electronic components provided possibility to construct more robotized vehicles. In consequence, it is possible to build vehicles of miniROV (mini Remotely Operated Vehicle) class, able to replace or assist the diver in monitoring and searching missions, due to the application of intelligent sensory and control systems able to detect underwater objects, avoid obstacles, indicate collisions or send the information about actual location and orientation of the vehicle. They are operated manually with the software installed on the console of the teleoperator. The teleoperator focuses only on reaching the desired area and on examining the images that are transferred by the vision system installed on-board. The development of automation technology made possible to replace the teleoperator with machine intelligence capable of making decisions autonomously. That recent progress resulted with the definition of a new class of underwater vehicles i.e. AUV (Autonomous Underwater Vehicles). AUVs are designed to collect data from the sensory system (such as recorded images and particular measurements) without the need of the operator.

This paper presents the robot Isfar, that belongs to the miniROV class with the ability to transform into the AUV class, enabling the manoeuvrability and large variety of applications of miniROVs combined with tetherless, autonomous operation of AUVs.

The word 'Isfar' means 'yellow' in Maltese language.

2. Overview of existing UUV solutions

Among many existing UUV solutions, these enumerated below belong to the most advanced group. It is worth mentioning that there are differences not only in the control systems and sensory equipment between these classes, but also on mechanical design i.e. ROV class vehicles are characterized by ‘crate-style’ design (see Fig. 1.) and AUVs are streamlined ‘torpedo-shaped’ with less motors but with wings (see Fig. 2.). In consequence, the maneuverability differs between these classes.

2.1. ROV/miniROV class

SeaBotix LBV series are miniROV class vehicles designed for rescue missions and to assist divers during their work. All of them are equipped with 4 to 6 thrusters, video camera and a console for the teleoperator. There are also many options e.g. a simple, attachable manipulator with replaceable grabbers or additional lighting. The maximum depth of vLBV950 is 950 m. Because of using the external power supply, attached to the console of the teleoperator (which is placed on the surface), the weight of these vehicles is very low (18 kg for vLBV950) [13].

Fig. 1. SeaBotix LBV300 miniROV.

VideoRay has several different models of miniROVs designed for underwater inspection of both sea and inland waters. These vehicles are upgradeable with many external components such as grabbers, cameras, imaging sonar, radiation detectors or water quality measuring devices.

The VideoRay vehicles are not equipped with an on-board power supply [14].

2.2. AUV class

HUGIN as a heavy AUV developed by Kongsberg Maritime (Norway) in 1990 with the co-operation with the Norwegian Defence Research Establishment [3]. More advanced versions are HUGIN 3000 (maximum depth is 3000 m), HUGIN 1000 (compact version of HUGIN 3000) and HUGIN 4500 (able to operate at the depth of 4500 m). HUGIN is designed for many applications in oceanography, environmental monitoring, underwater resource studies and also for military applications e.g. mine searching [4].

Remote Environmental Measuring Unit(s) (REMUS) developed in Woods Hole Oceanographic Institution in 1994 is a pioneer of an autonomous, compact, low-cost vehicle designed to collect environmental data to help understanding stability and change in marine ecosystems [1]. It is equipped with the acoustic-based navigation system, depth and temperature sensors. In the year 2000 REMUS gained many new capabilities during development, e.g. added Doppler Velocity Log (DVL), compass, gyroscopes [2].

Currently the Hydroid company sells REMUS for the commercial use [16].

Fig. 2. REMUS AUV.

Starbug is a vision-based AUV designed for seabed mapping by the Australian Scientific and Research Organisation. It is designed for environmental monitoring of the Great Barrier Reef. Starbug is equipped with visually-guided navigation system, pressure sensor, magnetic compass, IMU and GPS (used on surface) [5],[6]. The vehicle Isfar, presented in this paper has many similarities to Starbug.

2.3. Underwater gliders

Underwater glider is a subclass of AUV class vehicle that has a specific drive. Gliders propel themselves by changing buoyancy and using wings to produce forward motion. Buoyancy is changed by varying the vehicle volume to create a buoyancy force. Wing lift balances the across-track buoyant force while the forward buoyant force balances drag [6]. The vehicle that exemplifies glider class is **Seaglider** built at the University of Washington. It is equipped with temperature-conductivity-dissolved oxygen sensor and fluorometer [8].

Fig. 3. Seaglider AUV.

3. Isfar overview

Fig. 4. The general view of the Isfar (Lake Malta in the background).

Isfar is a prototype of a hybrid of the miniROV and AUV in single vehicle. The main goal was to build a low-cost, small vehicle able to serve as an universal platform for experiments with equipment (a number of sensors and actuators) and intelligent algorithms. At the same time, it should be able to execute searching and rescue missions in ROV mode with the teleoperator. The characteristics of the robot are following:

- area of operation: inland waters, both artificial and natural,
- maximum depth up to 15 m,
- external dimensions (0.6 x 0.9 x 0.4) m,
- weight (in air) 25 kg,
- tethered connection with teleoperator,
- high bandwidth communication protocol,
- maximum speed: 0.7 m/s (forwards), 0.36 m/s (backwards),
- manoeuvring capabilities: 5 DOF,
- batteries able to supply energy for up to 3 h installed on-board
- hybrid control system able to work with operator (with the use of a special console) and/or autonomously,
- sensory equipment: IMU (Inertial Measurement Unit), a depth sensor, a vision system able to work in two modes (in visible spectrum and in near-infrared) with lighting.

4. Mechanical construction

Isfar has three hulls. Hulls are attached to the frame made of flat beams. The space between the main hull and side hulls is filled with two fins. The third fin, placed beneath the main hull, takes the function of keel commonly used in boats (see Fig. 5.).

Manoeuvring motors with propellers are mounted at the ends of the fins. The elements of buoyancy drive are placed inside the side hulls. Main hull contains power supply module, drivers of the actuators, sensors and main control unit.

Hulls are made from yellow polyethylene PE80 that is highly durable against pressure and resistant to a moisture. The plugs, preventing water penetration, together with fins are made from white polyethylene PE1000. The transparent porthole for camera, made from thick perspex, is mounted at the front of the main hull. The frame is made from inox steel. Additional ballasts, composed of rectangular plates made from stainless steel, are mounted on the keel.

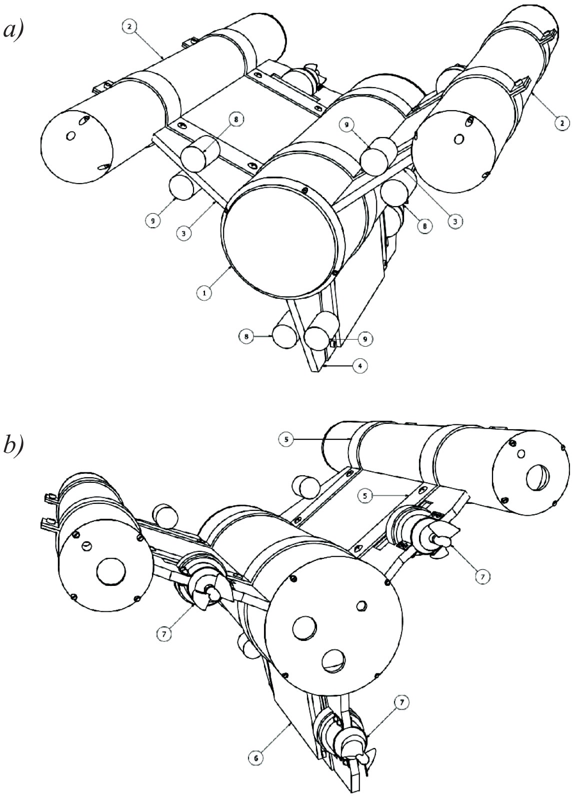

Fig. 5. Mechanical construction.
1 - main hull, 2 - side hull, 3 - fin, 4 - keel, 5 - frame, 6 - additional ballast, 7 - manoeuvring drive, 8 - lighting (NIR LEDs), 9 - lighting (cold-white LEDs).

Elements of the lighting are made from aluminium capsules with small perspex plugs. Specialised, underwater connectors are mounted on the back of the main hull. The wires connecting the floats, manoeuvring drives and lights with main hull are placed in small diameter hoses. The selection of a three-hull style of the robot forced, at the stage of design, accurate planning of quantity, placement, types and dimensions of all the internal components, since, at the stage of testing, there was no possibility to make modifications to the mechanics.

5. Hybrid control system

The three-layer control system was designed. The block diagram of the architecture of the control system is presented in Fig. 6.

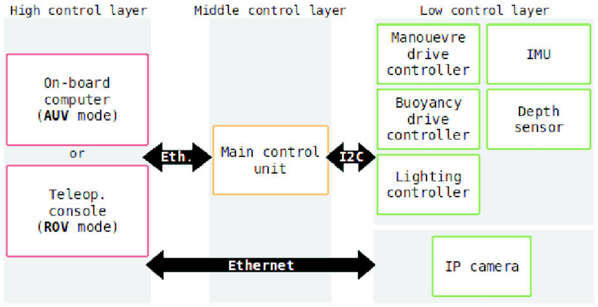

Fig. 6. The architecture of the control system of Isfar.

The use of the Ethernet as a main communication channel enabled the possibility to operate Isfar in two modes (ROV and AUV interchangeably). The Ethernet specification lets high channel capacities (there is a sequence of hi-res images transmitted from the underwater at the speed of 30 fps) and significant length of the tether connecting the robot with the teleoperator (in ROV mode). In order to make the robot operate in AUV mode, the selected AI algorithms must be transferred to the on-board computer.

In consequence, the missions that would be executed in that mode will make the human operator a passive observer only. There is no need to make hardware modifications to switch between these modes.

5.1. Low control layer

Low control layer consists of actuators and their drivers together with sensory systems.

The manoeuvring drive

In order to move backwards and forwards three DC motors with propellers were installed.
These motors, posing as the manoeuvring drive, come from Johnson L550 bilge pumps, thus there was no need to design the tight housing for the motors. The authors decided to use these motors for the sake of common availability and low price.

Each motor has the power of 36 W and maximum operating current of 3 A. The maximum torque of these motors is 50 mNm each. The two-blade propellers dia. 40 mm were used. The propellers were tested with the use of dynamometer, with the result of 6 N of thrust each (resulting the thrust of the robot of 18 N).

The drives were placed in the vertices of an equilateral triangle. In consequence, the way the motors were placed, the manoeuvring drive makes Isfar capable of:

- surging i.e. moving forwards and backwards,
- change of orientation i.e. heading angle and pitch angle (which is useful while ferreting during the searching missions).

The controllers of the manoeuvring drive were designed with the use of an Atmel AVR ATmega8L microcontroller and H-bridges embedded in ST Micro-electronics VNH2SP30 chip. Due to characteristics of the VNH2SP30 circuit, especially its low resistance of internal transistors, the drive is energy efficient. The driver is able to control the motors in two modes: in open-loop mode with Pulse Width Modulation or in closed-loop with current feedback (VN2HSP30 chip has an embedded current sensor). The experiments undertaken with the drive proved, that current is directly proportional to the thrust of the motor.

The buoyancy drive

The buoyancy drive consists of four piston tanks with the volume of 0.5 l each. The piston tanks hold a DC motors with transmission gears mounted outside.

In accordance with the Archimedes principle, the increase of volume of water inside the tank, causes the buoyancy force to change. With the special layout of piston tanks in the construction of the robot, the magnitude and sense of the buoyancy force can be controlled thus the drive enables:

- heaving i.e. motion along vertical axis (immersing and emerging),
- change of orientation i.e. roll angle.

The range of all the piston tanks is approximately ±10 N. The measured speed of the robot to emerge is approx. 0.2 m/s. The set point for the drivers is the position of the piston inside the each tank. The controllers are designed with the use of similar drivers such as were used in the manoeuvring drive i.e. ST Microelectronics VNH2SP30. The communication role is taken by the AVR ATmega8L microcontroller.

All the drives that were installed on the robot lets Isfar to be a nonholonomic robot.

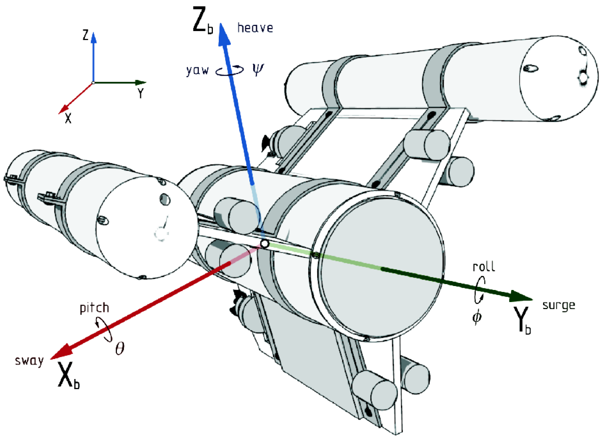

Fig. 7. Body frame axes and orientation angles.

The lighting

The lighting is based on high power LEDs. The lighting consists of six power diodes i.e. three cold-white diodes with the power of 3 W and three diodes emitting the near-infrared radiation with the power of 1 W and the wavelength of 850 nm. Each LED has mounted a star shaped radiator and a collimator. The capsules with diodes were mounted symmetrically (similar to manoeuvring motors i.e. at the basis of a triangle) in front of the fins mentioned above (see Fig. 5.)

The driver of the lighting is based on an AVR ATmega8L microcontroller and MBI1801 High-Power LED drivers. The brightness of the LEDs depends on the current controlled by MBI1801.

The on-board camera

The most essential part of underwater inspecting vehicles is a vision system sending the recorded sequence of images directly to the surface. Because Isfar is constructed for inland underwater inspection, the specialized vision system had to be designed, as the images are barely unreadable. To manage with this problem Isfar is equipped with the Intellinet 550291 network IP camera capable of recording images in insufficient light conditions. The camera is characterized by IR sensitive lenses which means that the spectrum of the light carrier is extended to a near-infrared band (wavelength up to 850 nm). The camera has an embedded Linux operating system installed, uses the Ethernet protocol to communicate, transmits images using Motion-JPEG or MPEG-4 format.

The parameters of the image recording such as brightness, contrast, saturation etc. are controlled via HTTP requests. Furthermore, the camera is characterized by:

- 1/3" Sony CCD sensor,
- image resolutions:
  720x576, 640x480 or 352x288,
- frame rate up to 30 fps.

Inertial Measurement Unit

In order to conduct the estimation of the orientation of the vehicle, the custom-made Inertial Measurement Unit is installed on-board. IMU consists of three digital gyroscopes measuring the angular velocities along axes of the body frame, and two 3-axis accelerometers. The gyroscopes are mounted on the board in the specific layout i.e. along three orthogonal axes. The work of gyroscopes is supported by redundant accelerometers, functioning as inclinometers, indicating the orientation of the board while it is perpendicular to the vector of gravity. By doing that the pitch and roll angles reset is made possible, thus the angle measured *via* gyroscopes are uncertain (the error is cumulative) because of the thermal noise. Additional function of accelerometers is to warn about collisions with obstacles. Three Atmel ADIS16060 iMEMS gyroscopes were used. The gyros are characterized by the range of ±80 deg/sec, 14-bit resolution and SPI output interface. The ADXL330 accelerometers work in the range of ±3g and have analog outputs. The main part of this sensory subsystem is an AT91SAM7S128 microcontroller based on ARM7 core. Its aim is to read the angular rates, convert them to floating point format, integrate (in order to calculate the angles) and transmit them to the middle control layer.

The depth sensor

According to Pascal's law, the depth of the immersed body is proportional to the pressure exerted to that body, thus the depth sensor is assembled with the use of the industrial pressure sensor WIKA A-10. The sensor is characterized by the analog output and by the range of pressure measurements approx. 5 ba, which means it is able to work at the depths up to 40 m. The work of this component is coordinated by an ATMega8L microcontroller.

It is worth mentioning that the low control layer has a modular design i.e. each driver or sensor controller was mounted on the separate board. In case of failure, only the damaged board has to be replaced. The software of low control layer is written in C programming language. The MCUs used at this layer are 8-bit AVR and 32-bit ARM7. The fault detection algorithm for I^2C bus was implemented both in the middle and low control layers.

5.2. Middle control layer

Middle layer of the control system contains only single device i.e. the main control unit. The purpose of that board is to connect and synchronise data between the high and low control layers. Simple regulation tasks such as buoyancy and heading control are also performed at this layer.

The main control unit is based on two integrated circuits i.e. the Ethernet controller and the ARM7 family microcontroller.

The Ethernet controller, Microchip ENC28J60 has embedded two layers of ISO/OSI model i.e. the Physical Layer (PHY module), and Data Link Layer (MAC module). The manufacturer implemented useful algorithms for collision detection, retransmission, packet filtering and checksum calculation. The controller communicates with processing unit via SPI interface.

The I2C bus allows up to 127 slave devices to be connected at the same time and makes the system using that bus universal and reconfigurable.

The communication between the high and low control layer is based on a protocol of simple messages built on the basis of the Ethernet protocol, making possible to control Isfar in real-time. At the Network Layer of the OSI model, the IP is used and as a protocol of Transport Layer - UDP. It is worth mentioning that datagrams are sent in a stream. The software of the middle control layer is written in C programming language. All the protocols of the 3rd and above OSI layers were implemented independently on the microcontroller.

5.3. High control layer

The high control layer complies with star network topology.

Two different types of devices are allowed at this layer: the remote console of the teleoperator and a supervisory computer with autonomous operation algorithms. It is obvious that these devices might work together at the same time, but only one of them works as an active driver and the remaining devices – only as passive observers.

The remote console (ROV mode)

The teleoperator has a console equipped with gamepad or joystick at his disposal. The main part of the console is a mobile PC running the graphical application that shows current image from under the water [13]. The GUI of the console application is designed on the model of HUD (Heads-Up Display) applied in the modern military aircrafts i.e. indicators showing the flight parameters do not cover the view in front of the vehicle, and the pilot does not need to turn his head to monitor them. The application is built using Python programming language and PyGame library. The application is multi-platform, it was tested under Windows and also under Linux operating systems.

The on-board computer (AUV mode)

The remote console might be replaced by the on-board computer in autonomous operation.

The robot would be able to work without constraining the motion tether then. Decisive algorithms implemented at this layer would be knowledge based and supported by the current data delivered by sensory systems, in particular camera and sonar.

The work at designing algorithms for the autonomous operation is currently under development.

5.4. Power supply

The power module of Isfar contains four Li-Poly batteries with capacitance of 5600 mAh each and with nominal voltage of 11.1 V. The choice of lithium-polymer accumulators is justified by their good capacitance to volume co-efficient. Usage of the PoE (Power over Ethernet) standard, and suitable contactor made possible to turn on or reset the robot only by plugging in the Ethernet RJ-45 connector to its socket.

6. Applications

The primary purpose of Isfar is to execute searching missions. As it is known, every mission requires the specialised and trained divers to work in very difficult conditions, often dangerous. Using robot that would replace the diver is justified.

Isfar is able to work significantly longer then the diver without emerging to the surface. Long diving periods are disastrous to the diver's health.

It is obvious that robots does not suffer from diseases that the divers might fall due to their work e.g. diseases resulting from the contamination of water environment.

Searching and reconnaissance missions are inseparable with rescue missions. The specialised groups of rescuers might be interested in such vehicles.

Another application of Isfar is inspection and cataloguing of underwater plants or objects e.g. monitoring underwater structures such as pillars of bridges or boat plating, which maintenance is critical.

Another purpose of Isfar is to map the bed of the lake or river and hence the robot may work at the service of environmental care and could search and indicate the location of the source of the contamination, especially with the use of NIR recorded images.

The robot could also assist in the archaeological research conducted under the water.

7. Summary

Taking to the account the current state of development of robots supporting humans, operating in difficult and dangerous environments, Isfar exemplifies vehicle that has still unique operational capabilities. The first experiments on Lake Malta in Poznan, confirmed the assumed operational parameters in underwater environment. At the moment, Isfar is ready for the execution of missions in ROV mode i.e. with teleoperator. The development work in the area of extending autonomy of the robot is in progress now.

Some conclusions can be drawn from the current design:

- In the vehicles like Isfar, the Inertial Measurement Units should work together with digital compasses (based on magnetometers), the DVL (Doppler Velocity Log) and GPS transceivers. The idea of using these components is surely worth considering, in order to improve the better localization, orientation and linear velocity measurements of the robot.
- The sensory system could be also augmented by using the multi-beam sonar making possible to scan or map the bed of the lake or river.
- There is also a possibility to make a fusion of recorded images by visual together with acoustic sensory systems' output.

The presented control system, due to its transparency and modularity could be applied to the other robots, not necessarily underwater.

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