AUV for Diver Assistance and Safety - Design and Implementation -

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***Abstract*—Diving as a profession and sport is and will be one of the most dangerous disciplines known by man. Water is not a natural habitat for humans and people need equipment to breathe underwater. Failure in the breathing apparatus, burst eardrum, decompression sickness and nitrogen narcosis are just a couple of problems which can occur during an ordinary dive and result in injuries, long-term illnesses or even death. The most common way to reduce the risk of diving is to dive in pairs. Use of the buddy system by scuba divers is a set of safety procedures that are intended to improve divers' chances of avoiding or surviving accidents underwater. When diving in pairs, divers can cooperate with each other and respond when uncommon situations occur. Having the ability to react before an unwanted situation happens would improve diver safety. This paper proposes a mechanical system which will be used with a scuba diver in a symbiotic link. The concept consists of a diver, an autonomous underwater robot (Buddy) and an autonomous surface robot (PlaDyPos) (Fig. 1) [1].**

***Keywords*—AUV, ROS, vehicle design, diver tracking, marine systems**

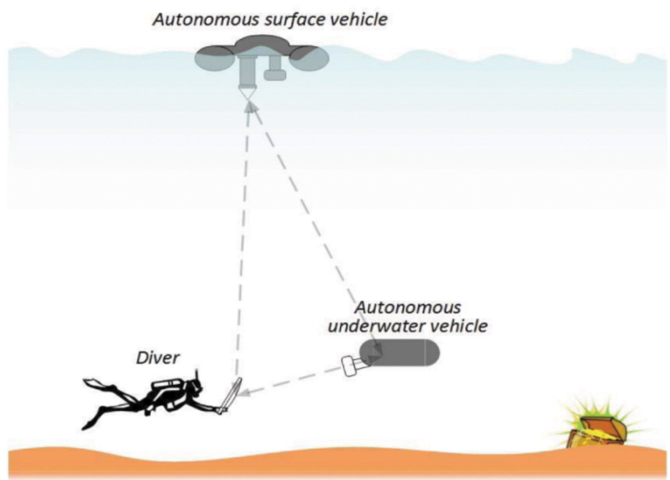

Figure 1. The CADDY concept

I. Introduction

A diver interacts with the companion underwater robot that maneuvers in the vicinity of the diver and reacts accordingly to diver actions. The autonomous surface vehicle communicates with the diver and the autonomous underwater robot via acoustic communication and shares the acquired data with the command center. The autonomous surface robot is also used as a navigation aid for the diver and the autonomous underwater robot.

As mentioned, the diver is equipped with the acoustic modem which allows diver tracking and communication. The diver tablet, located in a custom made underwater housing and stylus, gives the diver the possibility to exchange messages with the command center and, for the first time, to see its position on the map underwater. Full tablet functionality is preserved with the underwater housing and stylus which enables taking photos or videos, writing notes or playing games, reading a book and watching videos during the ascent. The autonomous surface robot provides a precise GPS position for both the diver and the autonomous underwater robot. It is also used as a diver buoy with the diver down flag since it is dynamically positioned to be above the diver. With four thrusters in a X-configuration it is over-actuated so it can move in every direction while maintaining desired heading. The autonomous underwater robot (Fig. 2) which design and control will be explained in details plays an important role in this system. It is equipped with a high resolution multibeam sonar and a stereo camera for detecting the diver's pose, an IMU and DVL for underwater navigation, a underwater tablet for interaction with the diver and a low light camera with tilt capabilities for, e.g. mosaicking, looking back, etc. Special attention is also given to the diver safety requirements.

Four thrusters are placed in a horizontal X-configuration allowing movement in every direction in the horizontal plane. Two thrusters are placed in front and back of the vehicle for depth control and it is also possible to pitch the vehicle powering the thrusters in opposite directions. The navigation, guidance and control (NGC) system is designed in ROS. Control is separated into a dynamic velocity controller and kinematic controllers for position and orientation. Position and attitude estimation incorporates asynchronous measurements from available sensors like DVL, USBL to localize the vehicle during underwater maneuvers. Additionally, the positions of the diver and surface platform are estimated on the vehicle during acoustic data exchange for complete situational awareness. High-level behaviours (primitives), e.g. diver tracking and guidance are achieved by combining available kinematic controllers. In addition to the hardware description a brief

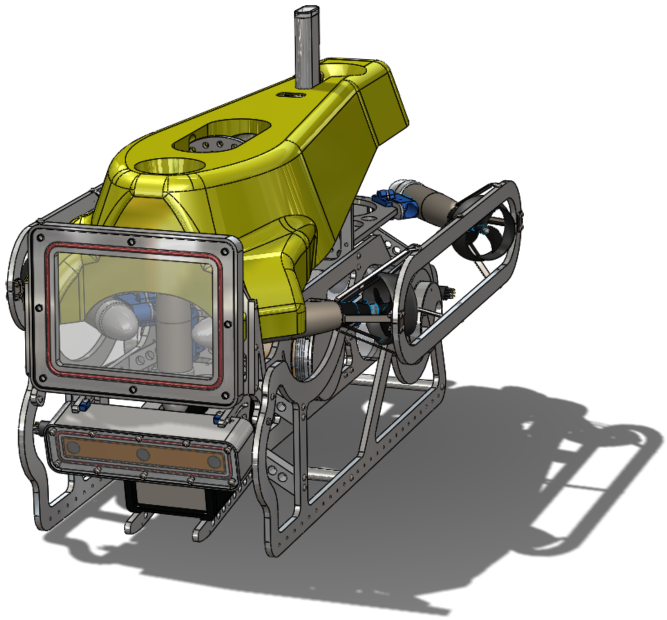

Figure 2. Autonomous underwater robot - Buddy

overview of the NGC architecture is given. This work is divided in three main sections:

- Hardware construction
- Electric assembly
- Software implementation

II. Hardware construction

The frame of the autonomous underwater vehicle is made of an engineered plastic (polyacetal, POM-C). All pieces were cut from 9 mm thick sheet of plastic and screwed together with stainless steel nuts and bolts. Hinges, lock nuts, flanges and mounts are made of Aluminum alloy. Overall dimensions of the vehicle are 1150x700x750 mm. Three waterproof Aluminum canisters contain electronics and the battery which will be explained in section III.

The vehicle carries a large variety of sensors. For navigation it uses:

- USBL - Autonomous surface platform and underwater vehicle have USBL beacons and diver has modem beacon. With the help of the GPS unit on autonomous surface platform, vehicle can get its GPS coordinates, as well as coordinates of the diver [2].
- IMU - 9 axis IMU gives attitude and assists the Kalman filter with movement data.
- DVL - Gives altitude as well as velocity in X and Y direction (speed over ground).
- GPS - Used for avigation on the surface.

Sensors for remote sensing are:

- Multibeam sonar - High frequency (3.0 and 1.8 MHz) sonar gives unprecedented high definition imagery of the diver from 0.7 m to 5 and 15 m, depending on frequency used.
- Stereo camera - 3-sensor multi-baseline monochrome camera is used for detecting divers pose when water visibility is high.
- Low-light camera - 0.017 lx color camera with 180° tilt mechanism located on the rear end of the vehicle is used for mosaicking and as rear view camera.

A. Thrusters

The underwater vehicle uses six thrusters for moving in five degrees of freedom (DOF). Four horizontal thrusters set in a X-configuration allow surge, sway and yaw motion. Two vertical thrusters provide control of heave and pitch. Of-the-shelf commercial thrusters were fitted with a custom made controller, heat sink and mounts. For extra cooling capability thrusters were filled with mineral hydraulic oil.

B. Underwater tablet housing

This section provides the description of the dedicated devices needed to interface the diver with the robotic platforms. Underwater tablet case was made of Polyacetal (POM-C) and tempered glass. It is situated in the front of the vehicle so that the diver can communicate with it. It uses a customized inductive pen for interaction. The main purpose of the casing is to hold a commercially available tablet that is used by the diver as an interface to the vehicle. The tablet case is designed in symmetrical form to implement 5 mm thick transparent tempered glass lids onto both sides of the housing. This allows for the use of the rear tablet camera and, due to stiffness of tempered glass, less sagging caused by external pressure. It uses star-grip knobs for clamping. Rear lid is fastened and independently sealed with the housing frame.

C. Diver safety

In order to ensure diver safety according to the requirements, two types of safety kill switches are implemented in the vehicle:

- Magnetic safety switches
- Haptic safety switch

There are five magnetic (reed) relays on the outer shell of the vehicle (Fig. 3). Two relays are in front, two on port and starboard sides and one in at the back of the vehicle. Magnetic safety switches are directly connected to the solid state relay which powers the thrusters. Relays are connected in series; by removing only one of the five magnets, the solid state relay cuts the power to the thrusters.

The haptic safety switch detects changes in IMU readings. If there is any deviation in one of the acceleration axes, e.g. diver pushes the vehicle back if it gets to close, the software automatically stops the thrusters.

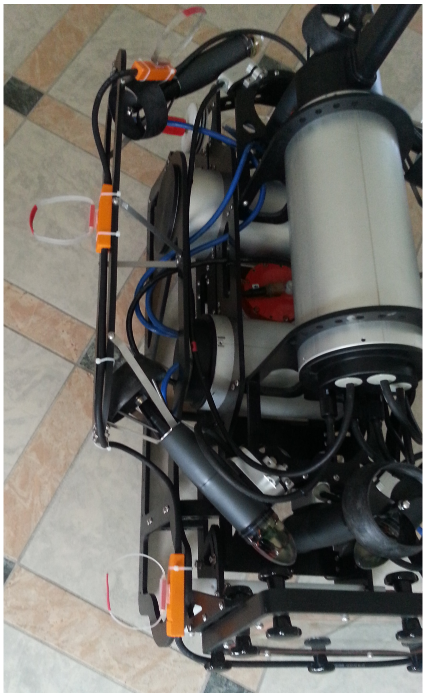

Figure 3. Kill switches installed on the vehicle

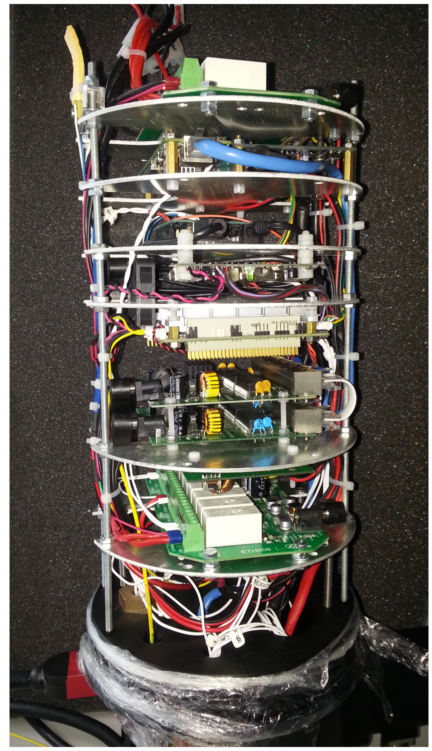

Figure 4. Master cylinder setup

III. Electric assembly

Buddy vehicle's electronics is divided in three canisters:

- Battery canister
- Master canister
- Vision canister

A. Battery canister

Battery with nominal voltage of 46.8 V and nominal capacity of 24.8 Ah is directly wired to 5, 12 and 24 V DC/DC regulators. Regulators are turned on or off via a magnetic switch which is controlled by a magnet outside the canister. When On/Off pins of DC/DC regulators are short circuited to ground regulators are turned off. This is accomplished by putting the magnet over the magnetic switch. When the magnet is released, DC/DC regulators are turned on. 24V DC/DC regulator feeds two 9V DC/DC regulators. 5V DC/DC regulator turns on the solid state relay used for disconnecting the power to the motors via kill switches. The battery is bonded to one cap of the canister with double sided adhesive tape to prevent movement and rolling inside the canister. Through the other cap four underwater cables exit to connect the Master and Vision canisters. There is an additional magnetic switch which is controlled by a magnet outside of the canister if in any case it is needed to completely turn off the battery or reset it if the battery management system (BMS) shuts itself down due to over current, low voltage, etc.

B. Master canister

The master canister includes:

- Fiber optic converter for communication with the surface.
- Gigabit switch
- Ethernet relay board for powering up thrusters
- Ethernet relay board for powering up CPU, DVL, USBL and GSM module
- PC104 embedded PC
- IMU
- GPS
- Wi-Fi antenna
- GSM module

Inside the canister is a rack connected to one of the caps of the canister for easy assembly or disassembly of the whole canister (Fig. 4). On the same cap there is a Wi-Fi antenna with a GPS module for communication and localization during surface operation. There is also an antenna for a GSM module. The GSM module can accept calls or SMS-es. After receiving a call or SMS the vehicle sends a SMS containing the current telemetry, e.g. GPS position, battery voltage, fault status, etc. The embedded PC is responsible for control of the BUDDY vehicle:

- Gathering and processing data from DVL, USBL, IMU, GPS
- Responding to commands and sharing telemetry data through fiber optic cable with the ground station for testing purposes
- sending commands to the motors

Fiber optic cable is connected to a fiber optic converter which is then connected to gigabit Ethernet switch. Overall intention is to have as much equipment as possible on the Ethernet connection. This makes equipment easily accessible for the user and allows for independent use of equipment. If some part of equipment is not on the Ethernet network, it is connected to an embedded computer via a serial connection.

C. Vision canister

This canister includes:

- Mini PC for acquisition of sonar, stereo and mono camera image
- Gigabit switch
- Ethernet relay board for powering up CPU, sonar and cameras
- 24/31 V DC/DC regulator for multibeam sonar

Electronics inside of the canister is assembled on a rack which is connected to one of the end caps for easy assembly.

IV. The NGC system

The NGC is designed in the Robot Operating System (ROS), [3]. ROS provides operating system services such as hardware abstraction, low-level device control, message-passing between processes, and package management. ROS by itself is a soft-real time environment however integration with real-time operating systems is available. The framework is well established in land robotics and has a broad range of supported platforms and sensors. Lately, the emerging use of the framework in underwater vehicle competitions like SAUC-E triggered higher usage in underwater robotics. It provides a platform for connecting application (ROS) nodes in a subscribe-publish manner. This inter-process communication infrastructure is well suited for modular development. Parts of the AUV control and navigation architecture are developed as ROS nodes, a self standing unit that has predefined inputs and outputs. In a sense a node is a black-box for other nodes, offering only a small interface for interaction. Exactly how nodes connect and interchange data in the background is handled by ROS.

The control layout is structure into a cascade of speed controllers and higher-level controllers as shown in Figure 5. The speed controllers control the vehicle dynamics making the higher-level controllers independent of the vehicle model parameters. The speed controllers are auto-tuned PI controllers with a feed-forward action:

$$\boldsymbol{\tau} = K_p(\boldsymbol{\nu}^* - \hat{\boldsymbol{\nu}}) + K_i \int (\boldsymbol{\nu}^* \hat{\boldsymbol{\nu}}) \mathrm{d}t + \boldsymbol{\tau_{ff}} \qquad (1)$$

where $\boldsymbol{\nu}^*$, $\boldsymbol{\nu}$ and $\boldsymbol{\tau_{ff}}$ are the speed set-point, speed estimate and feed-forward term, respectively. The control output are generalized force and torque values denoted with $\boldsymbol{\tau}$. The control layout follow the same principles as presented in [4] but with extension to heave and pitch DOFs. Notice that for non-linear dynamics the feed-forward term can be used for feedback linearization. High-level controllers that act in the primary loop of the cascade include position and orientation controllers. The controllers are design under the assumption of an ideal secondary loop controller in order to decouple

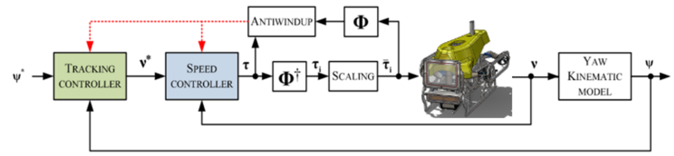

Figure 5. Cascade control layout

dependence on vehicle model parameters from the high-level controller auto-tuning. Controller are implemented as separate ROS nodes but are all triggered by the navigation filter output to achieve a consistent sampling rate across all nodes.

The ROS navigation node uses the thrust inputs and the dynamic model to estimate vehicle speeds and positions. The estimated speeds are used by the controllers. The benefit of this filter is that the cascade control layout can be applied even in cases where speeds are not directly measured. The EKF filter is designed to enable incorporation of additional asynchronous measurements from speed sensors without changing structure. This allows automatically fusing all available knowledge about the vehicle state to increase the final navigation precision without setting the requirement on the sensor suite.

V. Conclusion

This paper presents a concept with a diver, autonomous surface vehicle and autonomous underwater vehicle. Autonomous underwater vehicle can follow or lead the diver, thus helping the diver while performing tasks underwater. Underwater communication and localization is available for all agents via USBL system. Autonomous underwater vehicle is described in details with hardware and electric components for a better insight how system performs. The suggested software implementation was already validated on multiple vehicles but the heave and pitch extensions remain to be tested.

Acknowledgment

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