SAUC-E IUB Team

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Abstract

The SAUCE-E IUB team consists mainly of undergraduate and graduate students from IUB which is a private, independent research university founded in February 1999. The most basic vehicle parts, namely the hull, the batteries, the motors with propellers, and some sensors were generously provided to IUB by Atlas Elektronik. The submarine can be easily regarded as being composited out of a main hull, a nose and four long tubes. Those parts house the power system, the propulsion system, the low level controller called CubeSystem, a high level controller which is a car PC and lots of sensors. The low level control is based on the so-called CubeSystem.

The submarine uses analog as well as digital sensors. The two sensors that provide information about the depth of the AUV, namely the pressure sensor and the echo sounder, are both analog. The submarine has four tubes of nickel-cadmium rechargeable batteries which are connected in series such that they provide about 29 volt.

The software for the IUB AUV comes in two parts. The basic hardware control is done by the Cube software which is written in C. The AI software is running on the PC which uses SuSE 10 as operating system. It collects all sensordata from the cube as well as from the sensors directly attached to it.

1 Introduction

The IUB SAUC-E team consists mainly of undergraduate students from the IUB robotics club and graduate students from the IUB robotics group. The team leader Sören Schwertfeger is a graduate student in the Smart Systems program. The team is advised by Prof. Dr. Andreas Birk.

1.1 The International University Bremen (IUB)

The International University Bremen (IUB) is an innovative, forward-looking concept in the university landscape of Germany. IUB is a private, independent research university founded in February 1999, which tries to bring many of the best aspects of American higher education to Germany, including the classic bachelor's degree, which combines broad exposure to a variety

Figure 1: The IUB campus.

of intellectual traditions with solid training within a major field of study. The language of instruction is English.

IUB is a selective, private institution for the advancement of education and research. Students from over 80 nations are studying at IUB for their bachelor's, master's, or doctorate degree. This diversity is also reflected in the SAUC-E team. The fields of study and research cover engineering, the natural sciences, the humanities and the social sciences. The members of the IUB robotics club are predominantly undergraduate students of Electrical Engineering and Computer Science. The graduates in the team are part of the Smart Systems program in Computer Science. There are intense robotics research and teaching activities at IUB. This includes for example according courses in the final year of the undergraduate EECS program. Also, the graduate program Smart System offers a large variety of robotics and AI courses in every semester of the course plan.

Unlike any other German university, the IUB undergraduate studies are based on a residential college program. There are hence many different social, academic and sports activities on campus. These activities are organised in clubs that are completely run by the undergraduate students. The IUB robotics club is one of them. It was founded with the start of teaching and research activities at IUB in fall 2001. Members of the club already participated in various events, especially RoboCup competitions.

1.2 IUB Robotics

Robotics research at IUB focuses on Autonomous Systems. The expertise of the group ranges from the development of embedded hardware over mechatronics and sensors to high-level software. On the basic research side of autonomous systems, machine learning and cooperation are core themes of robotics research at IUB. The systems developed at IUB are used in various domains especially rescue robots [BC06].

Rescue robots can be highly valuable tools in urban rescue missions after severe disasters like earthquakes, bomb- or gas-explosions. The robots can be used to inspect collapsed buildings, to assess the situation and to search and locate victims. There are many engineering and scientific challenges in this domain. Rescue robots not only have to be designed for the harsh environmental conditions of disasters, but they also need advanced capabilities like intelligent

Figure 2: Two IUB rescue robots in a test arena in the robotics lab (left) and an IUB robot participating in a disaster drill involving hazardous materials (right).

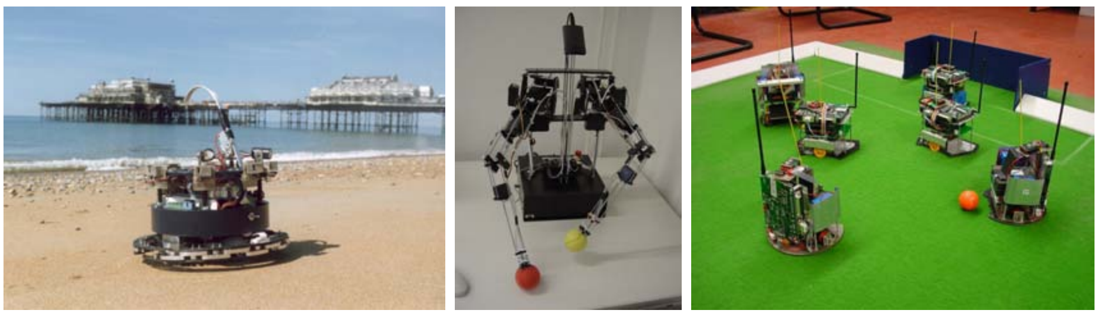

Figure 3: The expertise at IUB robotics covers autonomous systems from various domains. Work in the past includes behaviour oriented robots (left), a humanoid torso (center) and soccer robots (right). The autonomous underwater vehicle for SAUC-E is hence to some extent a completely new endeavour, though we expect that a lot of our general experience with autonomy can be also used in this field.

behaviours to free them from constant supervision by operators. Since 2001 the International University Bremen (IUB) is actively engaged in this research field [BCC+06] [Bir05] [BCK04] [BKR+02].

The IUB Rescue Robots are complete in-house developments based on the so-called CubeSystem, a collection of hardware and software components for fast robot prototyping. The development of intelligent behaviours is in addition to the robots' mechatronics a great challenge in this research area. The robot must for example autonomously detect victims and hazards. Special sensors like CO2 detectors and Infrared cameras can be helpful to detect humans, but they nevertheless require advanced techniques to enable even the most basic machine intelligence. This holds not only in respect to perception, but even more in respect to world modelling, e.g., in the form of learning of environment's maps. Hence recent projects of IUB robotics include the machine learning of the perception of humans in unstructured environments as well as the learning of 3-dimensional models of according environments.

In addition to rescue robotics, IUB robotics has the expertise of developing robots for various domains ranging from educational activities [ADB+00, BGK00] over basic research [BW02, BKS02] to industrial applications [BK02, BK01]. The underwater domain is a novel field for

Figure 4: Some of the most basic vehicle parts, namely the hull, the motors and the batteries, are based on parts from a so-called Seafox ROV that was provided by ATLAS ELEKTRONIK to IUB. The complete development of the electronics, the sensors, the onboard computer, the actuators, and software was solely done by the IUB team.

us, but we see the very interesting scientific challenges especially with regard to autonomy in this field [Yon92]. Underwater exploration is of tremendous interest from the industrial as well as from the scientific perspective, let it be in shallow coastal waters or in the deep sea. Examples include the exploration of seismic and volcanic activities [UOTG01], environmental monitoring [UAP97, Cra86], archaeological research [CNB00] and of course the exploration of natural resources [NYMM76].

2 The AUV Hardware

2.1 Core Vehicle Parts

The most basic vehicle parts, namely the hull, the batteries, the motors with propellers, and some sensors were generously provided to IUB by the Bremen company ATLAS ELEKTRONIK.

The parts belong to a so-called SeaFox ROV which is used as a mine identification and disposal[1] system. It is designed to be remotely controlled over an expendable fibre optic cable and to dive to a depth of up to 300 meters. The SEAFOX system is already in-service with the German Navy since 1998 and under contract with the Royal Swedish, the Royal Netherlands, the Belgian, and the US Navies. The vehicle itself is small (length 1.3 m) and light (weight approx. 43 kg). The maximum forward speed is six knots forward, which is of course not used during the competition, and less than one knot reverse.

The main reason for using these parts is simply cost as the project was solely started as a student project. The goal is to make a first step to explore the possibilities to carry over results from the autonomous land-based IUB robots to the underwater domain. The SAUC-E competition is a very good testbed for this purpose.

Though these core parts are in principle very nice, their main disadvantage is that they are laid out for a vehicle which is designed to cover longer ranges. It is hence fast but not extremely maneuverable, which gives a certain disadvantage for the tasks asked for at SAUC-E. As mentioned, budgetary constraints did not allow for any alternative solutions that are quite easy to conceive.

Picture 4 shows the hull and the motors with propellers.

2.2 Part List

The submarine can be easily regarded as being composited out of a main hull, a nose and four long tubes. Those parts house the power system, the propulsion system, the low level controller called CubeSystem, a high level controller which is a car PC and lots of sensors.

The nose section contains:

- Pressure sensor for depth measurement
- Heading sensor including pitch and roll sensor
- High-resolution sonar head
- Front camera

The middle section contains:

- Echo Sounder
- Vertical thruster mounted in an open ended cylinder perpendicular to the vehicle body
- Cube System
- PC
- PSU for Cube, PC and sensors

[1] Unfortunately the explosives used to destroy the mines have been removed before the vehicle was handed out to the IUB team ...

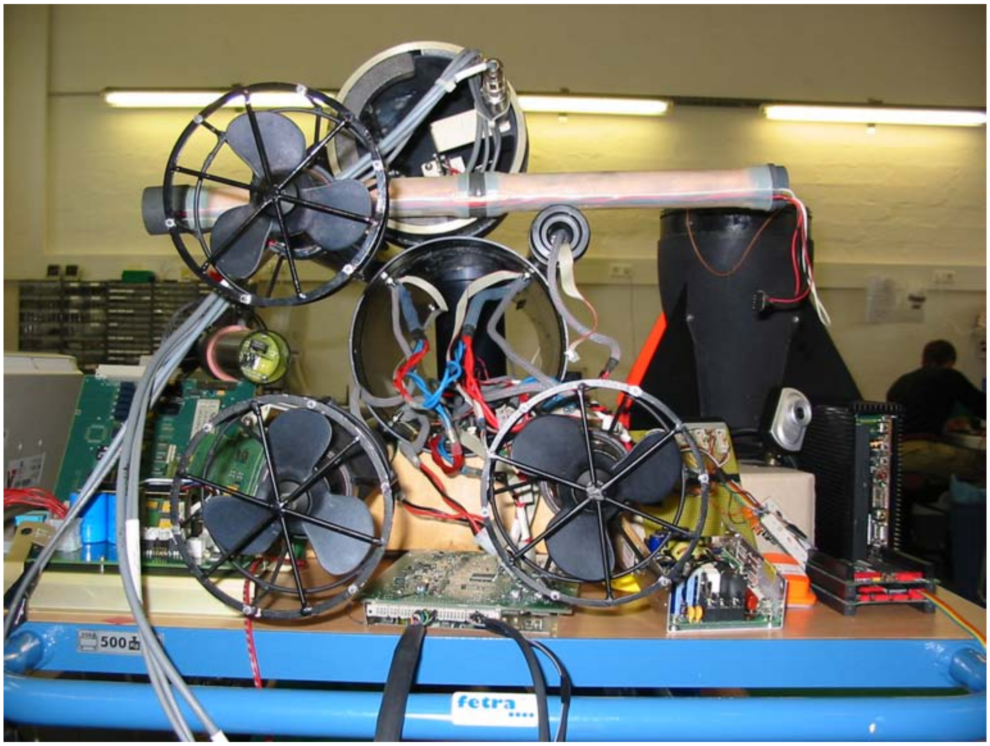

Figure 5: The disassembled vehicle. The old unused electronics is left of the vehicle. The sonar board which is used to control the seeking sonar is below the thrusters. The nose of the submarine with the sonar and the pressure sensor as well as one of the batteries is on top of the vehicle. Right of the sub is the new power supply, the orange gyro and a cube system. A first testversion of a Cube base-board is next to the car computer and in front of the two USB cameras. The back of the submarine with the four fins is also shown.

Outside, below the middle section the following is attached to the vehicle:

- USB camera
- Marker disposal system

Four battery tubes are attached to the middle section, each containing:

- Propulsion motor
- Propeller with guards
- Electronics for motor control
- Battery

The submarine is trimmed slightly positively buoyant, i.e. it comes up to the surface in case of some error. Thus the middle thruster has to be used to force the vehicle under water. The maximum power of the four propulsion motors is 350 W of which up to 280 W are usable due to PWM duty cycle limitations. The 3-blade propellers are protected by guards for safety while handling and also for preventing the fibre optical cable to be cut.

2.3 Low level controller

The low level control is based on the so-called CubeSystem. It is a collection of hardware- and software-components for fast robot prototyping developed in the IUB lab. It is also used in the EECS education at IUB. The main goal of the CubeSystem project is to provide an open source collection of generic building blocks that can be freely combined into an application.

The most basic parts of the CubeSystem are

- *RoboCube*: a special embedded controller, or more precisely controller family, based on the MC68332 processor
- *CubeOS*: an operating system, or more precisely an OS family
- *RobLib*: a library with common functions for robotics

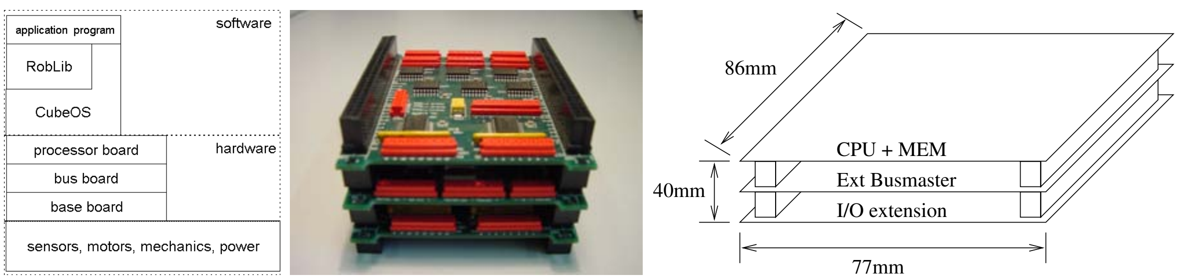

Figure 6: The structure of a CubeSystem application (left). A RoboCube processor-, bus- and I/O-board stacked together (center), leading to a compact controller hardware (right).

The general CubeOS and RobLib are collections of software components that can be customised and combined to a particular set of libraries suited for a particular application. The CubeOS has for example POSIX constructs to write realtime code. The RobLib provides for example generic functions for controlling motors via Pulse-Width-Modulation (PWM). The CubeSystem also allows quite some flexibility to adopt the hardware side to the actual application. The RoboCube or short Cube features some standard electronic components like the processor-, bus-, and I/O-board that are combined with a more application specific base-board. The boards are equipped with a special stacking connector that allows to put several boards on top of each other. The compact form factor of the boards and the stacking leads to a cubic shape of the controller (figure 6), hence the name Robo*Cube*. The organisation of the Cube architecture can be thought of in a tree-like manner. At the root is the minimal Cube, namely a processor-board which can be expanded by a bus-board. This new branch adds new functionalities like, e.g., UARTs and I^2C controllers that allow to expand to further branches, for example in form of certain sensors.

So, a CubeSystem application is a concrete instance of a collection of components, for example in form of a mobile soccer robot. The task for the IUB AUV team was hence to design a suited

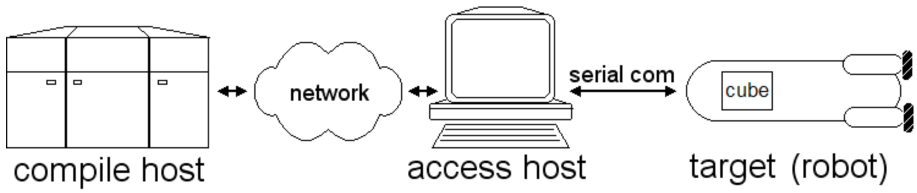

Figure 7: The CubeSystem programs for the AUV are developed and compiled on a compile-host, i.e., a Linux server where the proper cross-compiler and the libraries are installed. The binaries are downloaded via an access-host, typically an arbitrary PC, to the robot.

baseboard and low level software based on RobLib functions. The particular challenge is the number of motors, namely five, in contrast to the usual number of two on land-based robots. Furthermore, locomotion is harder as it is in 6D.

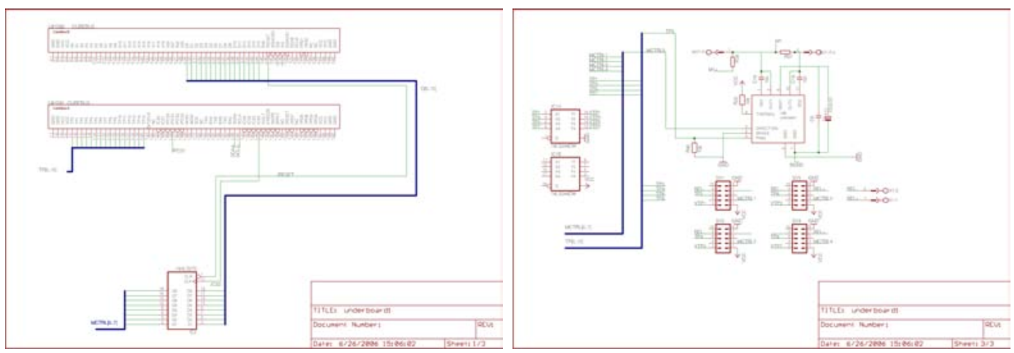

Figure 8: The schematics for a first version of a Cube base board for the IUB AUV.

The IUB AUV is just like any mobile robot a typical embedded system with an according development environment. The structure of the development environment is shown in figure 7. The CubeSystem is connected via a serial connection to the so-called access-host. This connection is a simple RS-232 cable. The AUV CubeSystem is programmed for efficiency reasons only in C. The generation of executables, i.e., compilation and linking, is done on a so-called compile-host. In doing so, the GNU tool chain with an according cross-compiler is used. The generic CubeOS and Roblib, as well as customised and pre-compiled instances, are also located on the compile-host.

2.4 High level controller

The RoboCube with its MC68332 micro-controller is not suited for any high-level computation that are required for fully autonomous control of an underwater vehicle. Like in many other IUB robots an additional PC is used as a so-called compute host, which is also dubbed “cognition” unit. For the IUB AUV, a Sumicom S625F car-computer is used as compute host (figure 10). This PC is a fanless computer with a Celeron M 370 at 1.5 GHz. It supports a standard 2.5” hard disk, runs on 12V, weighs about 1.5 kg, and it is very compact, namely 14.6 x 25 x 4.2 cm. It has a fair collection of interfaces, namely

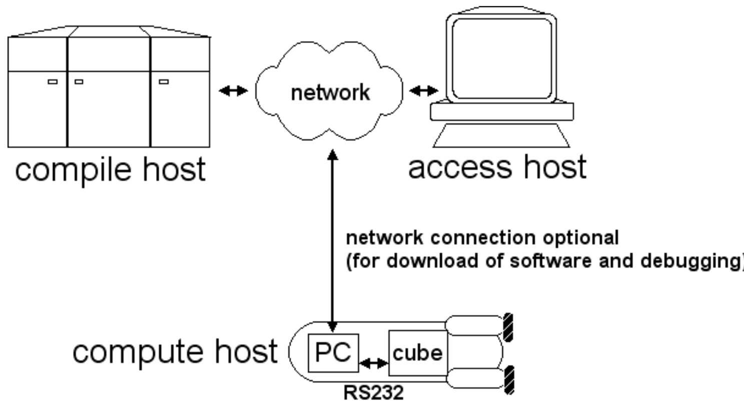

Figure 9: The computation requirements for a fully autonomous underwater vehicle go far beyond what the CubeSystem can do. Like on other IUB robots, a PC running Linux is used on the AUV as a "cognition" unit.

- front panel
  - 1 x IEEE 1394 Firewire port
  - 1 x USB 2.0 / 1.1 Port
  - 1 x MIC Port
  - 1 x Ear Phone output Jack
- back panel
  - 1 x RS-232 COM port
  - 1 x parallel printer port
  - 1 x RJ45 10/100Mb Fast Ethernet
  - 1 x Line-Out output Jack
  - 2 x USB 2.0 / 1.1 Ports
  - 1 x 15 pin VGA
  - 1 x 12v DC Power Jack input

For saving energy the optical drive, which is not needed under water, has been removed from the Sumicom computer. To be able to do some realtime debugging a fibre optic cable connects the PC inside the sub with a land based operator station. It provides a normal IP connection using of the shelf parts.

2.5 Sensors

The submarine uses analog as well as digital sensors. The analog sensors are connected to the Cube System which already provides several A/D converters. The two sensors that provide information about the depth of the AUV, namely the pressure sensor and the echo sounder, are

Figure 10: The Sumicom S625F as "cognition" unit on the IUB AUV.

both analog. The digital sensors are all connected via serial lines to the PC. The sonar head and the heading sensor use RS-232 while the two cameras are connected via USB.

The two RS-232 sensors are connected using USB to serial converters since the only RS-232 connector of the PC is used for the communication between the Cube and the PC. Since there are four devices to connect to the PC which only has three USB ports, the use of a USB hub is needed.

2.5.1 Heading Sensor

In the submarine the heading sensor named MTi from the company Xsens is used. This is a complete miniature inertial measurement unit with an integrated 3D compass. It has an embedded processor capable of calculating the roll, pitch and yaw in real time, as well as outputting calibrated 3D linear acceleration, rate of turn (gyro) and (earth) magnetic field data. The MTi uses a right handed Cartesian co-ordinate system which is body-fixed to the device and defined as the sensor co-ordinate system. Since the gyro is placed near the center of the sub the orientations provided by the device can directly be used as vehicle orientations.

The heading sensor is used to measure and control the roll, pitch and yaw of the AUV.

φ = roll[2] = rotation around X, defined from $[-180...180]$
θ = pitch[3] = rotation around Y, defined from $[-90...90]$
ψ = yaw[4] = rotation around Z, defined from $[-180...180]$

[2]roll is also known as: bank
[3]pitch is also known as: elevation or tilt
[4]yaw is also known as: heading, pan or azimuth

2.5.2 Seeking Sonar

The submarine has a seeking sonar which enables it to scan the surrounding for obstacles and their distance by emmiting soundsignals of 550 kHz and measuring the time it takes until the sounds echo comes back. The sonar covers up to 360 degrees since it is being turned by a motor in steps of one degree or bigger and it has a resolution of 1.5°. The range of the sonar is selectable to up to 80 meters. The sensor can also scan vertically with a coverage of ± 20°. The horizontal scan rate is about 60° per second at distances of up to 10 m.

The electronics needed to control the sonar and its motors is located on an extra board. This is the only electronics componend that was reused from the original Atlas SeaFox. It is connected to the PC via RS-232 and a USB to serial converter.

Figure 11: The nose of the submarine with the seeking sonar (the black cylinder underneath). The sonar board and the cables leading to it are also visible. The metal stick coming out of the top of the nose it the pressure sensor.

2.5.3 Pressure sensor

The pressure sensor measures the depth of the submarine below the water surface. It has an operating pressure range from 0 to 31 bar and a resolution of ± 10 millibar.

2.5.4 Echo sounder

The echo sounder measures the distance from the submarine to the ground by emmiting sound pulses with a frequency of 500 kHz and a width of 100 μs. The echo of this sound signal is being received and the travel time measured is then used to calculate the depth. The beam width is ± 3°, the accuracy ± 5 cm and the depth range 0.5 to 9.8 meters.

2.5.5 USB cameras

Two Creative NX Ultra USB cameras are used in the vehicle. They support a resolution of up to 640 x 480 pixel. Those USB 1.1 devices have a wide-angle lens which enables a field of view

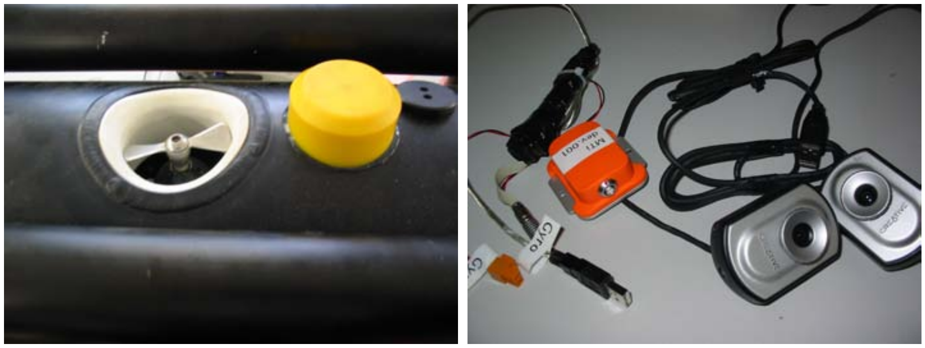

Figure 12: The left picture shows the middle section of the AUV from below. The middle thruster that forces the submarine downwards can be seen next to the yellow echo sounder. The orange heading sensor as well as the two USB cameras are shown in the right image.

of 78°. The camera at the bottom of the submarine is used to locate the circular bottom target and guide the submarine directly over it such that the markers can be released precicely. The front camera is used to search for the bottom as well as the mid-water target.

2.6 Power

The submarine has four tubes of nickel-cadmium rechargeable batteries. The six cells of a battery have a combined voltage of 7.2 volt and, when fully charged, 7 ampere hours. The batteries are connected in serial such that they provide about 29 volt. Fully charged batteries supply power for more than two hours of operation time. The IUB team uses twelve of those batteries such that discharged batteries can be recharged outside of the sub. The batteries are charged with the Charge Terminal Plus from Conrad Electronic. With those devices the charging of an empty battery takes about two hours.

Each end of the battery pipes is therefore easily sealable with metal catch. The upper seals contain a flashlight and an analog black and white camera which is not used by the IUB team while the lower ones are solid metal. A small industrial power supply is used to provide 12V and 5V which are needed for the PC, the Cube and the sensors. The ICP Electronics Inc. supply has an input range from 18V to 36V direct current and supports up to 10A on the 5V and up to 2.5A on the 12V line.

An external switch is used to cut off the power of the Cube system which immediately stops all motors since the relays are opened and now PWM is being generated.

2.7 Marker disposal system

The markers are designed to be very lightweight to ensure a stable position of the sub after the dropping of the marker. To have the least number of modifications to the hull it was decided to use a magnetic system to release the markers. The markers are made out of permanent magnets which can be pushed away from the vehicle using electromagnets once the submarine is over the target.

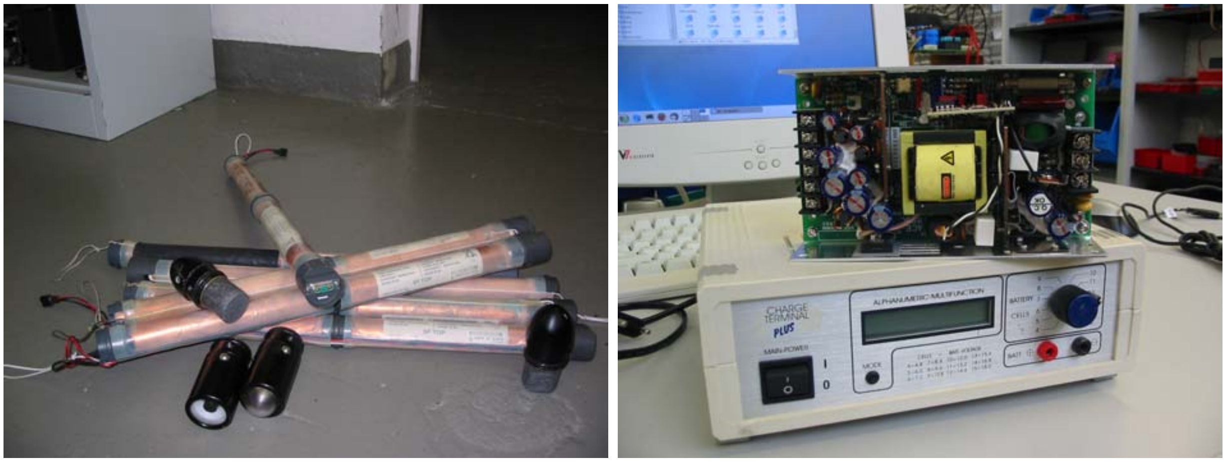

Figure 13: The left image shows some of the batteries together with the four seals. One of the chargers and the power supply unit for the submarine are on display in the right picture.

3 The AUV Software

The software for the IUB AUV comes in two parts. The basic hardware control is done by the Cube software which is written in C. It uses the CubeOS and the RobLib to generate the proper PWM signals, to decode the encoder signals from the motors and to access the analog pressure and echo sound sensors. The software running on the cube is also responsable for maintaining a certain depth which is set by the actual AI software.

The AI software is running on the PC which uses SuSE 10 as operating system. It collects all sensordata from the cube (depth and speed) as well as from the sensors directly attached to it. It uses the high-resolution sonar head to localise itself and the other objects in the basin. The front USB camera is also used to find objects while the sole purpose of the downlooking camera is to locate the target situated on the bottom of the tank. The software rescues some functions and libraries developed for other IUB Robotics projects and is written in C++. The Cube and the PC communicate over the RS-232 line using a special ASCII protocoll.

In order to successfully complete the mission the AUV runs an finite state automaton which defines which tasks should be solved next. For each task the same three important steps are accomplished. First the robot has to localise itself in the pool. Secondly the location of the targets with respect to the global co-ordinate system have to be determined. Lastly the AI software has to determine the actions that should take place next.

3.1 Self-localisation

The position of the submarine is computed using the seeking sonar, returning a distance to the nearest obstacle in a specified direction. Using the points determined in this way, the Hough Transform is applied, in order to find out the edges of the environment [DH72]. The distances to the walls of the environment determine the absolute position of the submarine in the horizontal plane. On the vertical axis, the position is determined using the pressure sensor and the vertical sonar, while the orientation of the submarine is determined with a heading sensor.

3.2 Target localisation

For the target location the front and bottom camera as well as the seeking sonar located in the head of the submarine are used. However, the sonar is somewhat slow, needing up to 6 seconds to give a new 360 degree view of the surroundings. This is why the cameras are the devices that the sub mostly relies on. They provide real-time information that is used to create a virtual map where the target is identified and pursued. Also based on this information the sub takes corrective measures to ensure the completion of the given task (going through the frame, finding the optimum place from where to release the markers, etc).

3.3 AI software

After acknowledging the position of itself and of the targets inside pool, this information is processed in order to obtain the next step. The AI behind the robot consists different operational states that correspond to different stages of the competition. According to the state the AI is and the input information a decision is taken. Also the AI comes with a self evaluation function that is used to determined if the stage of the competition is completed, only after this function evaluates to true the AI goes into the next state. Each "state" of the AI is developed as a separate stand alone module (since everything including the evaluation function is competition stage dependent) and then the robot is just forced to go through each module in a determinate order. Each stage is created using a feedback model, meaning that according to the input information does the most probable action and afterwards re-evaluates the situation. Since the information from the sensors is not extremely accurate the evaluation functions uses fuzzy logic to determine what needs to be done. A basic obstacle avoidance behaviour is also implemented to prevent the AUV from unintentionally hitting midwater objects [Ark20].

A proportional-integral-derivative controller (PID controller) is used to determine the PWM that is to be put to the middle thruster [AH95]. This way a stable depth can be accomplished even under difficult circumstances. The controller compares the measured values from the pressure and the echo sound sensor and calculates the difference of this values with a reference setpoint value.

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