Evolution of an Acoustic Modem for μAUVs

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Abstract—**The use of small autonomous underwater vehicles as mobile sensor networks is topic of many recent research projects. The swarm deployment of those robots enables a variety of flexible and low-cost use cases, such as port monitoring or marine research. For swarm interaction an underwater communication device is needed. For this purpose, we developed an acoustic modem , which fits into small autonomous underwater vehicles, is comparably cheap and offers reliable communication of up to $50\,\mathrm{m}$. During research with this modem, we discovered inadequacies, like low computing and insufficient transmission power. This paper presents an evolution of the modem, still beeing modular and low-cost, but having more computing power and an extended transmission range.**

I. Motivation

In recent years, many sensor network applications have been transferred into marine and especially into port areas. As an example, knowledge on the spatial extension of toxic pollution is important for the authorities to initiate countermeasures. Research projects like the *Clockwork Ocean* [4] measure finely grained temperature gradients in sea water. Using a static sensor network is inflexible, whilst using a single large mobile sensing device lowers coverage. Using inexpensive and very small autonomous underwater vehicles (μAUVs), however, offers large coverage and low cost at the same time. Recently, many small and cheap μAUVs have been developed, e.g. MONSUN [5], [7] and HippoCampus [3].

To enable swarm applications of these robots, robust underwater communication is needed. Communication devices already exist, but are either too large, too expensive or consume too much energy for this purpose. Devices that fit the needs are mostly closed source, and therefore do not allow the use in research on e.g. novel communication protocols or algorithms.

To face this, we have developed a small, low-power and inexpensive underwater acoustic modem [8]. It was designed for integration in MONSUN and allows reliable communication at small distances of up to $50\,\mathrm{m}$. Unfortunately, it has several inadequacies: (a) Due to its form factor it can not be easily integrated into other, possibly smaller, μAUVs like HippoCampus. (b) Its microcontroller is outmoded and slow, only allowing the software to run with some major deficiencies. Lacking computing power, sample rate and with that also the usable frequency band is limited. (c) The transmitter of the existing version only has a small transmission power, limiting the communication range in undistorted conditions to roughly $50\,\mathrm{m}$ – or less, if the signal is disturbed by shallow water, reflecting surfaces or the growth of underwater

plants. (d) Voltage regulators with a high quiescent current are used, resulting in low power-efficiency of $60\,\%$. (e) Due to incremental improvements and fixes many loose cable are used and many signals are routed across the whole PCB, both negatively influencing the signal characteristic.

Taking all the downsides together, we concluded that a complete redesign of the modem was needed, which we present in this paper. In contrast to the existing version our evolution is small enough to fit into many μAUVs, e.g. HippoCampus, which will be available for us, as it is also developed at Hamburg University of Technology. We maintain the existing modular design by identifying three main components and integrating each of them on one PCB each: mainboard, receiver and transmitter. To increase the computing power, allowing higher sample rates and the implementation of advanced algorithms, e.g. for medium access, we decided to use a new and modern, yet low-power processor family.

The output voltage of the transmitter is also increased to twice of the old value. This enables communicating within a higher range allowing the inspection of a whole port area by a big swarm of robots. Lastly, the efficiency of the modem is improved by integrating power down modes and more efficient voltage regulators. The details of the new evolution of this modem are presented in this paper.

II. System Design

In this section, the main design decisions for the new version are presented for every independent part of the modem.

A. Fundamentals

As the modular design of the existing modem was useful for quick and easy changes and improvements, the revised version should still be modular, yet reducing the number of parts and connectors. Regarding this we decided to split up the modem into three main parts: mainboard, receiver and transmitter. The mainboard holds the main processor, its power supply and communication interfaces to the computing unit of the robot. The receiver consists of amplifiers, an analog filter circuitry and an analog-digital converter. The transmitter contains a digital-analog-converter, a reconstruction filter and a power amplifier. All three parts of the modem are designed on a circular PCB with a diameter of $52\,\mathrm{mm}$. The circular shape allows an easy integration into MONSUN and many other μAUVs, as most of them are circular shaped, too. Our modem is still a low-cost device, the priced bill of material
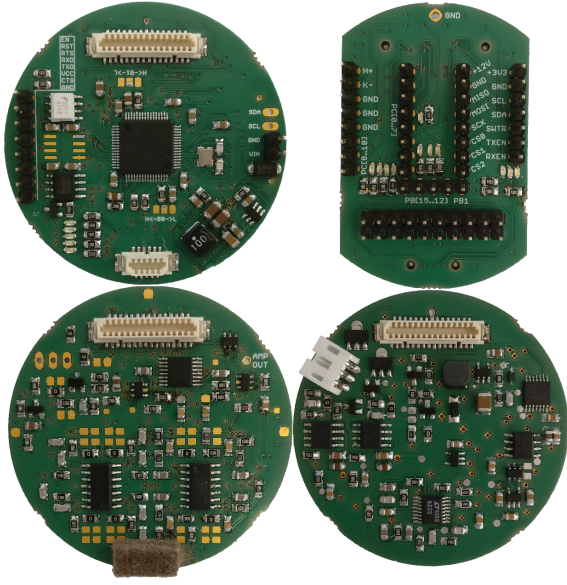
Fig. 1: The new evolution of our underwater modem. From upper left to lower right: mainboard, debug board, receiver, transmitter. The diameter of the boards is $52\,\mathrm{mm}$. All boards stacked together have a height of around $30\,\mathrm{mm}$.

(excluding hydrophone) is € 150 each, if at least ten pieces are built.

B. Mainboard

The existing version of the mainboard was powered by two voltage regulators with a high quiescent current of up to $7\,\mathrm{mA}$ each, resulting in an efficiency of only $60\,\%$. The AVR32 processor with its maximum frequency of $66\,\mathrm{MHz}$ is at its performance limit. Furthermore, the analog-digital (ADC) and digital-analog-converters (DAC) were integrated on the mainboard leading to long analog signal paths.

The new version of the modem mainboard is based on an STM32F446RE [10] microcontroller. It has a Cortex M4 core with a maximum clock frequency of $180\,\mathrm{MHz}$. With its flash memory of $512\,\mathrm{kB}$ it provides sufficient storage for the software-based implementation of the modem. We chose the 64-pin version of the microcontroller, as it is easily solderable by hand, still providing all needed peripherals like $\mathrm{I^2C}$, SPI, UART and enough GPIOs. For improved accuracy neither the included DAC nor ADC is used. A TPS54202 step-down converter at $3.3\,\mathrm{V}$ is used as power supply. It has a low quiescent current of $45\,\mathrm{\mu A}$. To protect the modem from voltage spikes possibly generated by the μAUV, all external signals are electrically isolated by using MOCD207 optocouplers and ADUM1202 isolating ICs. In addition to isolation the ADUM1202 also provides level translation, enabling a flexible use of the modem in μAUVs with different voltage levels.

C. Transmitter

The existing transmitter had an amplitude of $15\,\mathrm{V}$ at the output and the transmission range was limited to roughly $50\,\mathrm{m}$. As the output power is quadratically correlated to the output
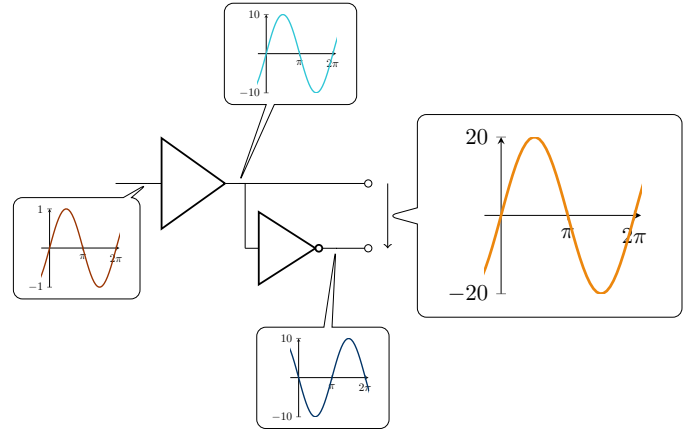

Fig. 2: Architectural overview of a bridge amplifier, with an exemplary gain at the amplifier of $20\,\mathrm{dB}$.

voltage, we had to increase the amplitude of the output to achieve a higher transmission range. To increase the amplitude, a negative voltage power supply is needed, capable of generating the maximum peak power of the transmitter. With a maximum frequency of $75\,\mathrm{kHz}$ and a nominal hydrophone capacitance of $6\,\mathrm{nF}$, a power of $4.5\,\mathrm{W}$ is needed for an amplitude of $40\,\mathrm{V}$. These power supplies are either expensive, cannot deliver the needed current or have a large footprint. A bridge amplifier solves this problem. Only a positive voltage has to be generated which is fed into an inverter. Placing the load between the non-inverted output and the inverted output gives twice the voltage generated, resulting in a higher transmission power. The architecture of such a bridge amplifier is shown in Fig. 2. Our bridge amplifier is built with two OPA55x [11] supplied by a voltage of up to $40\,\mathrm{V}$, the voltage amplitude is therefore limited at $80\,\mathrm{V}$. For low-power-applications or short ranges the transmission power can be adjusted. An LT6222 quadruple amplifier is used for two purposes: Three amplifiers are used as a 6th-order reconstruction filter, low-passing the signal generated by the DAC. The remaining amplifier is used as a pre-amplifier, generating the input signal to the power stage. The amplification factor can be adjusted using a digital potentiometer.

D. Receiver

The receiving part of the existing modem worked well in real world tests, so the basic architecture was kept for this second modem revision. The receiver still consists of multiple stages: a pre-amplifier, an 8th-order high- and lowpass-filter and a power amplifier. To adjust the gain, a multiplexer was used to switch an array of resistors on or off . This approach occupied nine GPIO pins of the microcontroller and the single steps of adjustment were coarse. Approaching these two drawbacks, a digital controllable potentiometer, the AD5142A, is used to adjust the gain in the new version. It is controllable via the $\mathrm{I^2C}$ bus, using only two GPIO pins. These pins can also be used to communicate with other $\mathrm{I^2C}$ devices, for example to adjust the gain of the transmitting part too. The
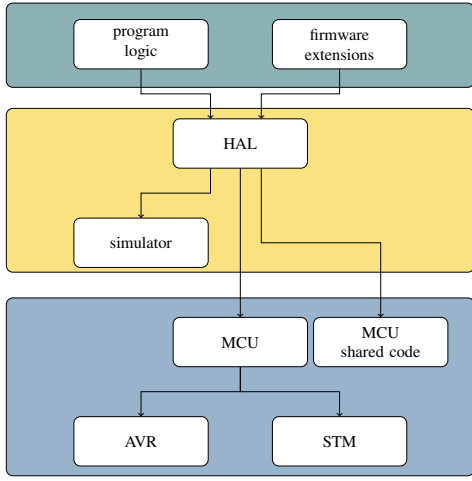
Fig. 3: Architectural overview of the modem software

AD5142A has a resolution of 8 bit, allowing the gain to be adjusted from a minimum value of $46\,\mathrm{dB}$ up to a maximum value of $104\,\mathrm{dB}$. It is adjustable in steps of at least $2\,\mathrm{dB}$ over the complete range.

E. Software

The software for the modem contains many hardware specific parts, like interfacing with the peripherals. No separation between functionality and hardware existed, so the same software used for the AVR could not be used with the STM microcontroller. Since the already existing modems should still be used for student projects or field tests, a software compatibility with the revised version is needed. The hardware-dependent parts have to be encapsulated from the hardware-independent parts. To achieve this goal, all hardware specific functions have been extracted from the original software into a hardware-abstraction-layer (HAL). Its architecture is illustrated in Fig. 3. The HAL provides functions like sending and receiving data over UART or I^{2}C and is transparent to the user. Timers and communication with ADC and DAC are also abstracted, allowing to easily change hardware parts without changing the program logic. In addition to that, there is also a simulator, which allows it to run the program logic on any computer without the need for having the actual hardware available.

III. EVALUATION

This section evaluates the performance of the newly designed parts of the modem and compares them to the existing version regarding frequency gain, computing power and energy efficiency.

A. Mainboard

To compare the performance between the AVR microcontroller and the STM microcontroller, a firmware version with the same functionality has been flashed to both of them. A GPIO is pulled low when the processor is idle. At the beginning of every interrupt, the same GPIO pin is pulled high again, indicating that the processor is active. Using this method, the reception of an arbitrary $16\,\mathrm{B}$ packet has been recorded. The AVR is idle at $47.2\,\%$ of the complete time of reception. The STM improves this value and is idle at $60.6\,\%$ of the reception time. The time gained can be used to activate a sleep mode or to use a higher sampling rate. At a first glance the improvement looks not very remarkable. During a packet reception some tasks have to be done once and in hard real-time, like decoding the packets header or preamble detection. This took $142\,\mu\mathrm{s}$ on the AVR and now only takes $38\,\mu\mathrm{s}$ on the STM processor. This leads to an empty sample queue in $84.4\,\%$ of the time compared to $66\,\%$ before.

The calculation of the maximum sample rate achievable by both microcontrollers is hard, because of the non-deterministic occurrence of certain events and the time overhead caused by them. Therefore the maximum sample rate has been determined by incrementally increasing until the system was not able to reliably receive packets. With the STM sample rates can be twice as high compared to AVR.

The power consumption of the new mainboard has been analyzed by measuring the voltage across a $3.3\,\Omega$ shunt. The supply voltage was $7.4\,\mathrm{V}$, which is the nominal voltage of the used 2-cell lipo battery. For testing purposes a $16\,\mathrm{B}$ long packet has been received, and the whole process of reception has been recorded. If no sleep modes are used, the mainboard and its power supply consumes around $210\,\mathrm{mW}$. Entering the sleep mode while the sample queue is empty, results in an average power consumption of $144\,\mathrm{mW}$. The previous mainboard had a power consumption of $280\,\mathrm{mW}$.

B. Transmitter

To evaluate the output power of the transmitter a sine waveform has been applied to the input of the amplification circuit. The frequency was swept in steps of $400\,\mathrm{Hz}$ from $400\,\mathrm{Hz}$ to $100\,\mathrm{kHz}$ and in steps of $10\,\mathrm{kHz}$ from $100\,\mathrm{kHz}$ to $500\,\mathrm{kHz}$. The input amplitude was $1.5\,\mathrm{V}$ with an offset of $1.5\,\mathrm{V}$, using the full range of the used DAC8830 at $3.3\,\mathrm{V}$ supply voltage. Figure 4 shows the output power of up to $32\,\mathrm{dBV}$. The increase of transmission power inevitably led to a higher power dissipation in the operational amplifiers. Due to the small size of the PCB and the ICs, the power amplifiers heated up to over $70\,^{\circ}\mathrm{C}$ after a couple of seconds sending. This is still in the allowed temperature range stated in the datasheet, but led to glitches in the amplified signal. All our tests were done in free air, so the temperature rise will likely be more significant after integration into an μAUV. Changing the package of the amplifier or adding heatsink can help to solve this problem.

C. Receiver

The power consumption of the receiving circuit has been measured in the same way as the mainboard, with the same supply voltage of $7.4\,\mathrm{V}$. We used a mainboard PCB without a mounted microcontroller allowing it to include efficiency of the voltage regulator in the measurement without measuring the microcontroller's current. The receiver consumes $10\,\mathrm{mW}$ when it is disabled. If all components of the receiving circuit
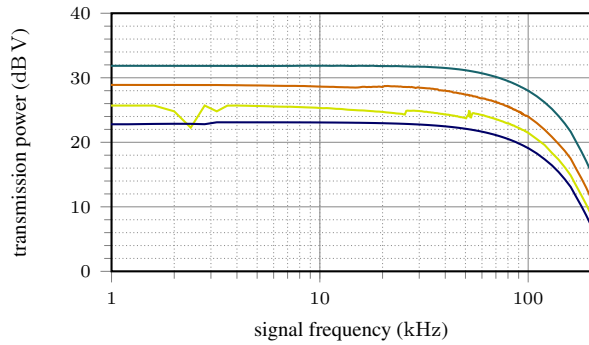
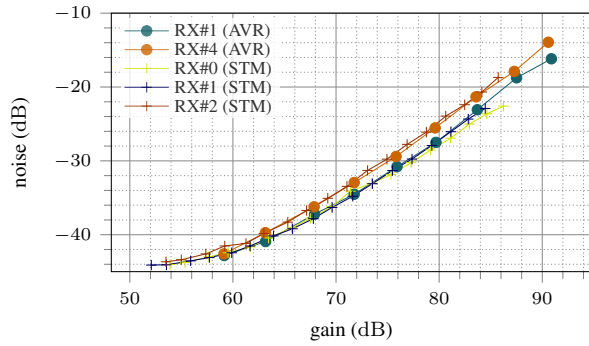Fig. 4: Output transmission power of the transmitter at different gains

Fig. 5: Recorded noise at different gain settings of the receiver.

are turned on, it consumes $120\,\mathrm{mW}$ in total. In addition to the power consumption, noise of the filter stages has also been investigated and is shown in Fig. 5.

IV. RELATED WORK

Several other devices have been developed during the last years. Most of the commercially available products are too expensive for integration into small and cheap AUVs. The Evologics S2C M HS [1] costs around € 8000. The modems produced by Linkquest, offer a high communication of up to $1000\,\mathrm{m}$, with a simultaenously high data rate of up to $7000\,\mathrm{bit/s}$. Beeing more than three times heavier than the HippoCampus as well, they are not suitable for an integration in μAUVs of that size. Another manufacturer is Teledyne Benthos, offering multiple devices with data rates of up to $15\,\mathrm{kbit/s}$. Unfortunately they are too big for an integration to μAUVs as well. In addition to size and costs issues none of the commercial devices allows the access to lower layer components, making the use impractical when it comes to research of modulation schemes or MAC protocols.

In contrast to the commercial available off-the-shelf modems, multiple devices have been developed by different research groups from around the world. The acoustic modem presented in [6] by Nowsheen et al. is a software-defined radio, offering a high data rate. However the demodulator is only available in MATLAB, making it unsuitable for integrating into real world robots. The WHOI micro modem [2] offers

a low energy consumption in receive modem and a large transmission power. The data rate is up to $5400\,\mathrm{bit/s}$, which would be sufficient for communication between swarm members. Unfortunately the price is in the range of the commercial devices. In [9] a comprehensive comparison of many different acoustic underwater modems can be found. We are currently not aware of any modem that is as small as our modem is, simultaneously offering an adequate data rate and a price in the three-digit range.

V. CONCLUSION

In this paper we presented a revised version of our small and low-power underwater acoustic modem. In contrast to the existing version, the new version is much smaller, allowing a flexible installation in many μAUVs, like MONSUN or HippoCampus. The microcontroller provides more computing power, making it either possible to increase the sampling rate or to activate sleep modes during active waiting times. Using sleep modes is not useful at all in the existing version, due to the high quiescent current of the voltage regulators. This problem is now solved by using low-power switching supply sources. The modem software was completely restructured, making it easy to include or change new hardware parts in the future. Next, we will further analyze the issues we found during the building process. As stated in Section III the heat dissipation has to be further investigated. In a next step, outdoor tests with the modem integrated in robots are on our agenda.

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