A SUBMARINE LOW-POWER SHIP PROPELLER STRAIN MEASUREMENT SYSTEM

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Abstract - *In this work the development of a custom submarine data acquisition system for the measurement of ship propeller strain is presented. The system measures the strain applied to 120-Ohm quarter bridge strain gauge sensors. It supports up to 15 acquisition channels, each with its own sensor, signal conditioning and 10-bit A/D converter, sampled at 500Hz. The system features all necessary analog and digital subsystems needed to perform the signal conditioning, acquisition and data storage. The main features of the system include low power consumption using sophisticated power management, compact design based on a multi-processor architecture, high measurement accuracy, low-cost and robust autonomous operation. The system can be easily extended for applications where a telemetry system with stand-alone operation is needed.*

Keywords – Data Acquisition, microcontroller, strain gauge.

1. INTRODUCTION

The custom data acquisition system presented in this paper was designed for the measurement of strains on a plastic ship propeller. The aim of the project was to perform some evaluation tests based on measurements of the strain applied to several points of the propeller while the ship was sailing.

A special plastic propeller was built and the sensors were fit in it during its fabrication process. A custom data acquisition system was developed to meet the special requirements of this project. It was installed inside a watertight cone of the propeller and it was constantly connected to the sensors.

The system was rotating along with the propeller, blocking any cable connections for power supply or online communication between the system and the measurements supervisor. For data transmission alternative solutions were considered, including the use of slip rings, radio, ultrasound and optical data transmission. The first solution could not be realized, as it was hard to modify the propeller axis in order to install the slip rings. The radio transmission was difficult because the system was operating underwater and this solution would demand excessive power resulting in huge batteries hard to put in the propeller cone. Ultrasound communication was not possible as the engine of the ship also produced ultrasounds and it would critically affect the performance of data communication. Finally the optical solution was difficult to implement, as it required extra metal assemblies hard to build around the rotating propeller.

Consequently the system had to operate autonomously, using batteries. It should be programmed offline with the set of measurements to carry (called a timeplan) and it should store the measured data on a memory inside the system.

The system's software was designed to minimize the risk of experiment failure. All recorded data should be transferred after the end of the experiments (offline) to a host PC, using an underwater connector and software preventing data loss.

2. SYSTEM DESCRIPTION

The data acquisition system is based on a multi microcontroller design, using three microcontrollers instead of one. It is divided into three subsections. Each section has its own microcontroller and a group of 5 sensors is connected to it.

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By dividing the circuit into three parts it was possible to minimize the risk of total failure if one or two microcontrollers stopped functioning. Such a failure could occur due to the vibrations produced from the propeller rotation. If such a failure would occur, the system would operate with the sensors connected to the working microcontrollers.

The block diagram of one channel of the data acquisition system is shown in Fig.1.

2.1 The Analog Subsystems

As illustrated in Fig.2, the front-end of the analog circuitry for each channel is the strain gauge sensor (Sn). The sensor is powered by its own stabilized power supply (+3.3V). Any 2-wire or 3-wire 120-Ohm strain gauge sensor can be supported without any hardware modification to the system.

Each sensor features its own analog section. The analog section includes a high performance low noise (and high Common Mode Rejection Ratio - CMRR) differential amplifier (15x), a programmable gain amplification stage (1.1x-21x), a final amplification stage (10x), two offset calibration stages and an anti-aliasing filter.

Prior to the design of the described system, there had been some theoretical calculations and simulations of the experimental propeller and its expected behavior. These results were used in order to calculate the gain factors of the amplification stages. The simulation provided the expected minimum and maximum strain at the exact points of the propeller where the sensors were installed. The amplification stages are designed so that their combination produces a 0-5V output voltage swing at sensor variations when the sensor strain varies between the minimum and maximum calculated values. It should be noted that for a successful experiment it is essential for the A/D input not to exceed 5V. Due to the system architecture, it is possible to adjust the amplification factors in order to measure strain exceeding the simulation values up to 300%. This is achieved through the programmable gain amplifier; if the results of one set of measurements indicate overload on the A/D input, it is possible to change the amplification factor to a lower value and successfully repeat the set of measurements. Thus, the used technique guarantees efficient use of the dynamic range of the A/D converter and eliminates A/D input overloading.

The first stage of amplification (A1 in Fig.2) is implemented using a high-accuracy and low noise differential amplifier. This amplifier is set to provide a 15x voltage gain.

The analog section has two stages for zero-offset calibration. The first stage (O1 in Fig.2) provides bridge offset error correction. It also performs thermal compensation and corrects any errors introduced by the differences in the sensor bridge resistors. Since two amplification units follow this calibration stage (A2 and A3), it acts as a coarse calibration stage in contrary to the second calibration stage (O2), which performs fine calibration.

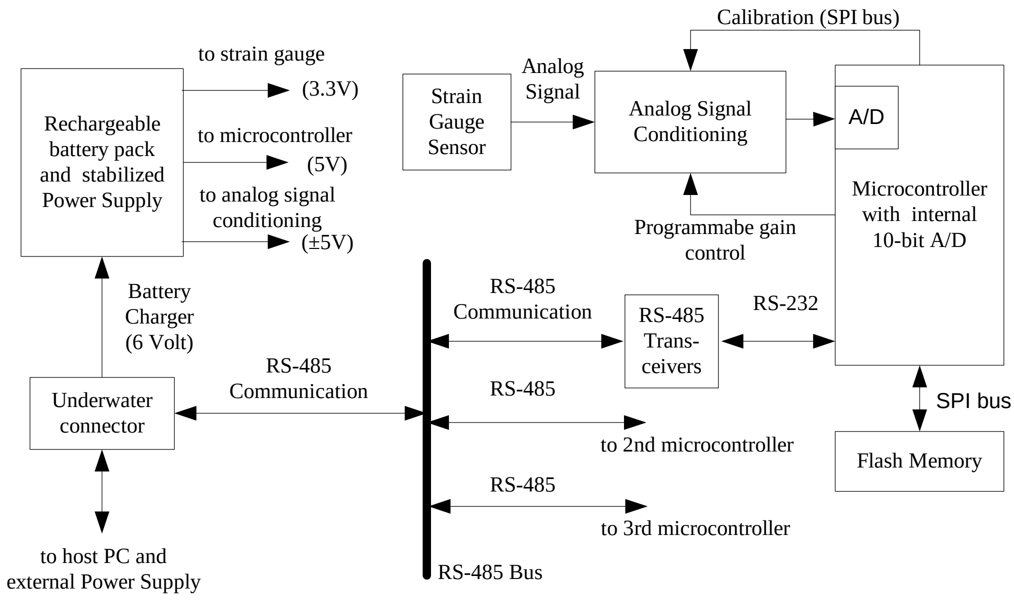

Fig.1 - The block diagram of the measuring system

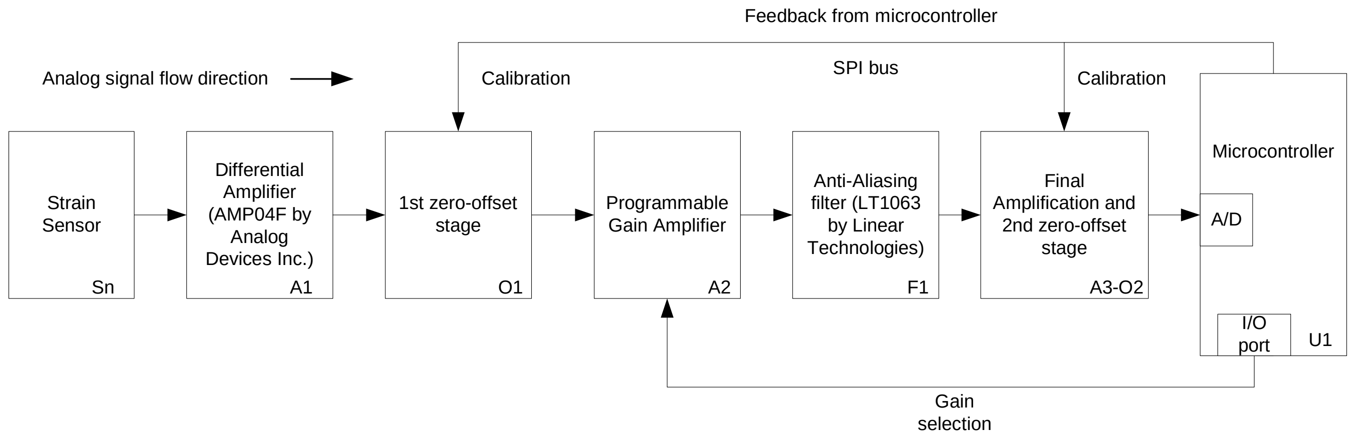

Fig.2 - The block diagram of the analog subsystems

Following the coarse calibration stage, a programmable gain amplifier (A2) is used providing the necessary output swing for efficient use of the A/D converter dynamic range. The amplifier gain is digitally selectable among fixed gain values (x1.1, x1.2, …, x21). These values were selected according to the accuracy demands of the experiments to be carried and the A/D dynamic range demands, as previously stated. The amplifier is implemented using a low-noise operational amplifier and a digital multiplexer / demultiplexer for the gain selection circuit.

As each channel is being sampled at 500Hz, a 250Hz anti-aliasing filter (F1) is used before the A/D converter. The used filter is a 6^{th} order low-pass Butterworth filter. Since the maximum output of this filter is limited to 4V, a final amplification stage (A3) is required in order to make efficient use of the A/D converter dynamic range. A second zero-offset calibration stage (O2) is also integrated in this amplifier. The amplifier (A3–O2) allows the output to swing from 0V to 5V, shifting it to 2.5Volts when no strain is applied to the sensor.

The offset correction on stages O1 and O2 is achieved using digitally controlled potentiometers. This ensures high reliability and stability of the analog section, as it is being immunized to vibrations and mechanical shocks, which critically affect the performance of their analog equivalents. It also achieves thermal compensation on the bridge and provides offset correction even when the initial strain on the sensor is not zero. The offset correction takes into account all possible offsets introduced by the various stages, thus calibrating the whole analog path.

For better performance over noise, additional 1^{st} order filtering between stages F1 and A3-O2 is used to ensure high frequency noise cutoff and to minimize the crosstalk between the digital and the analog section.

The measuring system is powered using high capacity Lead-Acid batteries. All power lines are stabilized with low-dropout IC regulators. This type of batteries was chosen because of their very good discharge characteristics: the output voltage of a Lead-Acid battery remains stable until the battery is almost fully discharged. A set of measurements showed that two 2.7Ah Lead-Acid batteries in parallel and a 1.3 Ah battery in series (for the negative power supplies) could power the system in data acquisition operation for approximately 4 hours. This duration is several times greater than the maximum time of recorded data the system can hold (46 minutes). Of course in idle state the batteries can power the system for several days. Finally this type of batteries does not require sophisticated charging circuitry, resulting at a lower cost compared to other types of rechargeable batteries.

During the development of the system it was decided cost reduction of the analog components by moving any offset error correction to the digital domain. Instead of very expensive amplifiers and accurate resistors that would result in less error and easier calibration, it was decided to use less expensive equivalents and perform additional correction via software. The cost of the system was also reduced with the use of common available microcontrollers instead of expensive DSPs and external A/D converters. Also the components were selected so that their power supply demands were kept as low as possible. In this system the power supply was reduced to 50mA per microcontroller and 6mA for each analog channel signal conditioning while each sensors demanded 25mA.

2.2 The Digital Subsystems

The described system is based on three PIC 16F877A microcontrollers. Each microcontroller collects data from 5 external analog lines. The lines are scanned in series, using the microcontroller's internal 10-bit high precision A/D converter. Each microcontroller features its separate external flash memory with a capacity of 64 Mbits. Since the sensors are sampled at 500Hz, each microcontroller produces a bitstream of 10bits*500Hz*5channels which corresponds to 25 KBps. The bitstream is directed to the external memory of the microcontroller, which is connected to its SPI lines. The memory capacity permits sampling at the given rate for about 46 minutes. The microcontroller's SPI outputs are also connected to the digitally controlled potentiometers of the analog subsystem used for zero-offset calibration. Furthermore the SPI lines of one microcontroller are connected to the programming input of a real-time clock. As the number of connected SPI peripherals exceeds the fan-out of the microcontroller SPI outputs, these lines are buffered for driving and protection reasons.

All microcontrollers are synchronized for data acquisition start and stop through the real-time clock. The clock can be programmed by only one microcontroller. Its output is connected to the interrupt input of all the three microcontrollers. When an interrupt occurs, it is acknowledged at the same time by all microcontrollers, synchronizing their data acquisition. The clock is programmed to generate an interrupt for the start and an interrupt for the stop of the acquisition.

Every microcontroller manages the power to its analog section. When the system is not performing data acquisition it is not necessary to power the analog subsystems and the microcontroller can switch their power off, saving energy. When acquisition has to begin, the microcontroller turns analog power on and waits for 10 seconds in order to reach thermal and electrical stability. After this waiting period, the microcontroller starts data acquisition.

The microcontrollers are connected to a common RS-485 bus, which can be interfaced to the serial port of a host PC. This connection is necessary before each experiment in order to provide the set of measurements the system must carry on (timeplan), to configure the gain at the programmable gain amplifiers, to monitor the system's status and to download any previously recorded data to the PC. The communication bus between the microcontrollers and the PC is operating at 115200bps. For the communication a special software driver for the PC was written along with corresponding software for the microcontrollers. Also extra hardware was used to interface the RS-232 output of the PC to the RS-485 bus.

The communication software also features a protocol that can detect any transmission errors via correction codes (CRCs) and request over the data packets that contain errors. In case of CRC error detection, the wrongly received packet is requested over until it is correctly received, unless the user chooses to ignore it.

According to the user's request, the PC each time sends a command to either one or in some cases all microcontrollers and waits for a response. The waiting period is limited by an appropriate for the requested operation timeout. If no response is detected, the PC either retries the operation or aborts it. The user is always notified about the progress of his request.

Throughout this process the external PC is considered to be the master of the data transmission. Each microcontroller is identified on the RS-485 bus by a unique ID (ID#1, ID#2, ID#3). All microcontrollers can be accessed from the PC simultaneously sending a command to ID #0 (multicast command). In responding to a multicast command each microcontroller waits for its predecessors to complete their operation. This command is useful to determine any malfunctioning microcontrollers as they fail to respond resulting in timeout.

Transmitted packets from the PC have a common header, including the microcontroller ID and the requested command, followed by the appropriate data and the packet CRCs. The response packet shares a similar format. Care has been taken so that no ambiguities occur, i.e. when received data resemble to microcontroller commands. The data communication is half-duplex: each request from the master PC is followed by the response of the corresponding microcontroller(s).

The operation of the host PC is achieved through custom software, for the Operating System of Microsoft® Windows® 98 / 2000.

2.3 Operation of the System

As stated in the introduction, due to the underwater operation of the system it was impossible to maintain a continuous data link between the PC and the data acquisition system. Thus, the operation of the system is *timeplan* based. It is accomplished by providing up to eight different timeplans of constant data acquisition per programming. These timeplans are uploaded to the microcontrollers through the connected host PC during programming phase. Each timeplan provides the starting point and the duration of the experiments and it is used to program the real-time clock. The system once programmed can be disconnected form the PC and operate according to the timeplans. The total amount of acquisition data cannot exceed the capacity of each microcontroller memory (64Mbits). In case where an invalid timeplan is uploaded, the system will perform as many measurements as its total memory permits, and will skip the rest.

During programming phase, the system is connected to the PC through an underwater pluggable connector. At this phase it is also possible to perform recharging of batteries.

Before the beginning of each experiment, all of the channels have to be calibrated. At programming phase the PC sends a special instruction to each microcontroller requesting zero-offset calibration. During this procedure any short or open-circuited sensors are being detected. The results of the calibration command are sent to the PC and presented to the user. The user can also manually calibrate individual channels and perform data acquisition; the acquisition results are displayed on the host PC. Furthermore he can set up each programmable gain amplifier and obtain information regarding the condition of a microcontroller.

After the timeplan programming, the communications cable between the PC and the system can be safely disconnected. By that time the system enters autonomous operation, following the timeplan. During data acquisition period, the system will discard all incoming commands from the serial port. After the end of the experiments the system can be connected to the PC.

Before the beginning of a timeplan execution, the whole memory is filled up with the value FF (HEX). After the end of a timeplan the system must be connected to the PC and the newly recorded data can be downloaded. This download must be performed before a new timeplan is sent to the system. At the given baud rate of 115200bps, it takes about 15 minutes for every microcontroller to transfer its data to the PC, assuming that its whole available memory has been recorded. Otherwise the data transfer needs only the necessary time to download the recorded amount of the memory.

The data downloading is performed with 264 bytes long packets, along with a 5 byte header and 4 CRC bytes. If a CRC error or a timeout occurs, the packet is requested over. After 5 retries the PC software notifies the user, allowing him to select either to continue requesting, ignore the damaged packet or cancel the procedure. This way the user can skip parts of the memory that do not respond and continue with the rest (an auto-ignore function is also provided). At the end of data reception, a data file (with extension *.dat) is created containing the downloaded data. Memory areas corresponding to ignored packets are written as FF (HEX) so they can be easily determined later.

Since the A/D conversion is performed with a 10-bit resolution and the memory is organized in 8-bit words, a packing of the data is required in order to save memory space and to speed-up downloading: the MSBs of each 4 bytes are stored in 4 sequential memory addresses and the remaining 2 LSBs of each of those 4 bytes are packed and stored in every 5^{th} memory address. At download time memory contents are transmitted in this form.

Before data downloading, it is essential to obtain the Table Of Contents (TOC) of the memory. This TOC contains the number of executed timeplans, and the exact memory address of the beginning and end of the data for each timeplan. TOC information is stored in each microcontroller's internal flash memory. This way the TOC information is not lost in case of battery discharge. Battery discharges do not affect any recorded data either as they are also stored in flash memories.

The TOC information is obtained through a special command sent from the PC. If the TOC had not been recorded due to serious damage of the microcontroller's internal circuitry but the microcontroller is able to communicate with the external flash memory, it is still possible to receive the recorded data. In this case the whole memory has to be downloaded and scanned by software so that recorded (non FF) memory areas are determined. These memory areas correspond to any successfully performed acquisition who's TOC was lost.

The received TOC is stored in the PC in form of a plain text file (extension *.toc) so that the user can easily see what the system has actually recorded.

After the data reception, additional software must be used to descramble the data file. This software takes input from the corresponding TOC and data files and creates new files saving the data according to the sensor and timeplan they belong to. At the end of this procedure, a new folder has been created containing one file for each sensor and each timeplan, resulting in 5 files per timeplan for every microcontroller.

Each output of the descrambler program is a plain ASCII text file making it easy for the user to examine the results and determine any obvious problem (i.e. signal overflow in a sensor). Also the output files are compliant with all existing DSP software permitting direct use of such advanced mathematical tools, i.e. MATLAB.

Development Testing & Standard Tests

Before the end of the project, the system had been thoroughly tested over a long period of time. It was also submitted to several testing in a pool filled with water. All tests were conducted using standard 120-Ohm strain gauges of the same type, without the propeller blade assembly.

CONCLUSIONS

In this work a design and development of a strain gauge telemetry measuring system is presented. The telemetry system was designed for strain measurements on a ship propeller. It can be used for highly accurate strain measurements in cases when autonomous operation is needed. The features incorporated to the system are:

- Compact design based on a multi-processor architecture
- Low power consumption using power management
- High measurement accuracy
- Low cost due to architecture and component selection
- Robustness
- Autonomous operation

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