# Enabling multiple robotic functions in an endoscopic capsule for the entire Gastrointestinal tract exploration

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***Abstract*— Commercial endoscopic capsules are passive. Nevertheless, active capabilities such as active locomotion, drug delivery or biopsy, among others, can now be offered with the aid of robotics. New robotic functions require additional electronics for control purposes, as well as for the sensors and actuators. To avoid increasing the capsule size as a consequence, it is useful to incorporate all the electronics into the minimum number of elements, preferably in a single ASIC. This paper describes the ASIC included in a robotised capsule with the abovementioned active functions. The ASIC is a system-on-chip (SoC) integrating all the electronics needed to control the other electronic elements in the capsule. It also enables the movement of two BLDC motors, illuminates the exploration region and focuses a liquid lens used to achieve advanced vision capabilities. Details of the complete system integration are also given.**

## I. INTRODUCTION

Wireless capsule endoscopy enables the gastrointestinal (GI) tract to be explored without causing pain or discomfort to the patient. Currently available wireless capsules are passive. They comprise a vision system that illuminates the exploration area and acquires images, and a transceiver to send the acquired data to the outside [1-3]. Actuating enhancements are critical in order to achieve disruptive therapeutic performance in the field of capsular endoscopy. This paper describes the SoC used in the first wireless endoscopic capsule that has active robotic locomotion The liquid lens offers advanced vision capabilities by allowing focusing.

Figure 1 shows a picture of an eight-legged capsule. Legged locomotion is one of the capsule's features as regards active movement [4]. The detailed system architecture of the capsule is presented in Figure 2. The capsule is powered by an internal battery that supplies 3.3 V, and which is recharged via an external RF power source. To enable active locomotion the capsule is provided with two brushless DC motors (BLDC) which are connected to the eight mini-legs. As can be seen in Figure 1, the legs are mounted on the body of the capsule. With the movement produced by the motors, the legs are expanded or collapsed, thereby enabling movement of the capsule. The capsule is also provided with four LEDs to provide white illumination, a monolithic 320 x 240 active-pixel RGB/grey level camera-on-a-chip sensor [5], a liquid lens that enables the focus function, a bidirectional RF link, a RF power source, and a central control unit (SoC). In specific scenarios where diagnosis or therapy is required an additional module can be connected. The SoC controls all these modules.

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Fig. 1: Capsule without plastic cover. The capsule is equipped with legged locomotion and illumination. Capsule size is 10mm x 33mm.

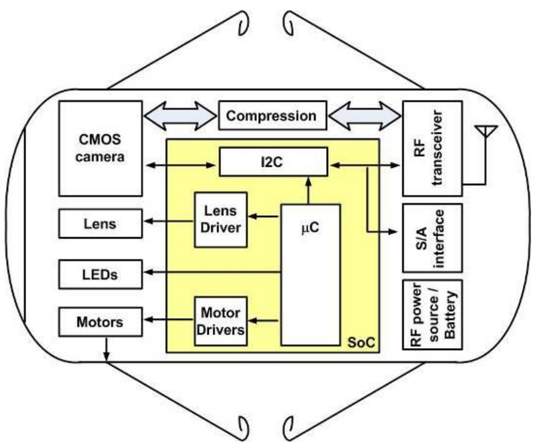



Fig. 2: System architecture of the capsule.

## II. SoC DESCRIPTION

The SoC (Figure 3) measures 5.1 mm x 5.2 mm and is implemented in a 0.35 um high voltage CMOS process of AustriaMicrosystems. A high voltage process is required because the liquid lens is operative when driven with a voltage between 30 V and 50 V. The chip is biased at 3.3 V and higher voltages are generated on-chip when required. The chip operates with an external clock of 10 MHz. The SoC is larger than those used in reported systems [6-7], mainly because of the integration of analogue drivers (Figure 3). For robotic active locomotion, mm-sized transistors are needed to efficiently manage currents in the 100 mA range. Despite its size, however, the chip fits perfectly in the capsule area and provides a better solution in terms of area and final assembly than would the use of separate chips for integrating digital and analogue/power functions.

Figure 4 shows the architecture of the SoC. The main block is the embedded 8051 microprocessor, which acts as the control unit. The processor is provided with specific peripherals to control the different capsule elements. This approach reduces the workload of the processor and allows power to be managed dynamically through enabling/disabling functions in the capsule.

The microprocessor comes with 2 kB of SRAM data memory and 8 kB of SRAM program memory. The capsule has to be programmed each time that it is powered up because the whole integrated memory is volatile.

The programming process is carried out by the boot loader (BL). This consists of a digital circuit that interprets and sends to the memory the data received via a serial input.

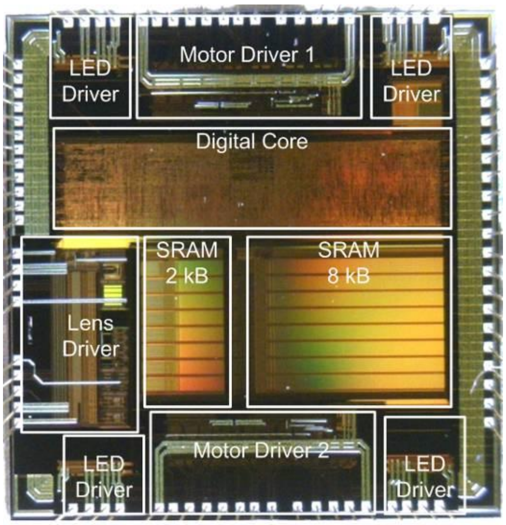



Fig. 3: Photography of the SoC.

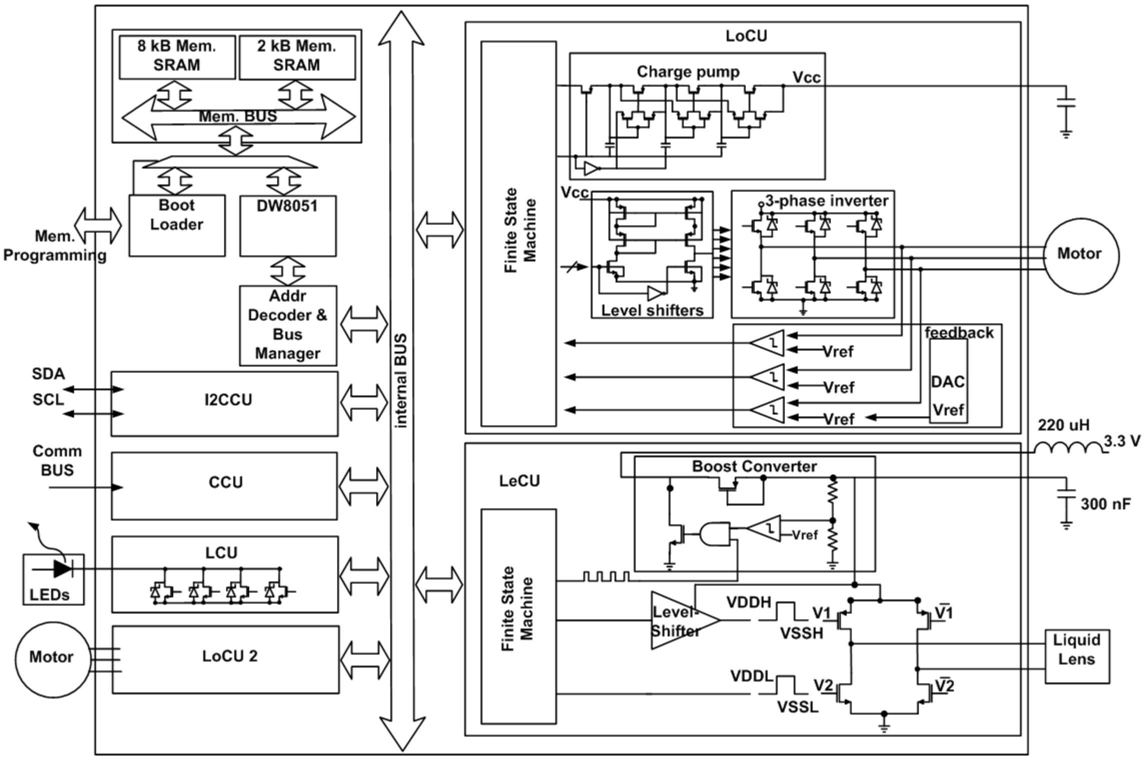



Fig.4: Architecture of the SoC and detail of the motor and lens drivers.

The motors are controlled by the locomotion control unit (LoCU), which is similar to that described in [8-9]. The LoCU comprises the analogue drivers for each motor and a digital finite state machine (FSM), whose functions include control of both motor start-up and the stationary phase. A sensorless control strategy is used in the driving. Figure 4 shows a detailed view of the analogue driver in the LoCU. A three-phase structure is used to drive the motor. The three-phase structure is powered at 3.3 V. The maximum current demand in each phase (100 mA) occurs during start-up. The three-phase structure is based solely on NMOS transistors so as to provide more robustness for latch-up. The transistors are operated with gate voltages of 5 V, which allows smaller transistors to be used than in the case of 3.3 V driving. The 5 V bias is generated by a Dickson charge pump and is applied to the gates through level shifters. The sensorless control is based on the measurement of the back electromotive forces (BEMF) generated at the motor. Thus, the motor driver is also equipped with a feedback stage. In the feedback a comparator senses each motor phase. One R/2R digital-to-analogue converter (DAC) generates the voltage reference for the comparators.

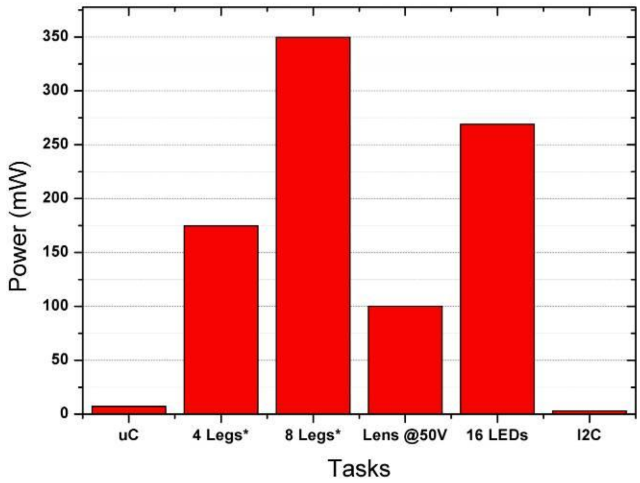
Focusing is performed by the lens control unit (LeCU), which is similar to [10]. The focal of the lens is changed when it is driven with a PWM signal of amplitude between 30 V and 50 V. The impedance of the lens depends on the frequency of the driving signal, and a PWM signal of 1 kHz has practical utility. The LeCU diagram is the same as that of the LoCU, i.e. it comprises a digital FSM and an analogue module. Figure 4 shows the diagram of the LeCU. The main element of the lens driver is an H-bridge (HB), which has two HV-PMOS transistors and two HV-NMOS transistors. The two outputs of the HB are connected directly to the liquid lens electrodes. The supply voltage of the lens driver (up to VDDH = 50 V) is generated by a DC-DC boost converter integrated into the SoC. Two high-voltage level-shifters are needed to adapt the driving signals to the operating gate voltages of the HV-PMOS transistors. Under normal operation the LeCU focuses the liquid lens by changing the frequency of the boost converter control signal. The voltage supply is then changed between 30 V and 50 V.

The basic functions of the capsule (i.e. illumination, communication and vision) are also controlled by the SoC. The GI tract is illuminated using four LEDs. These LEDs are turned on/off by the LED control unit (LCU). The LED driver is comprised of eight transistors in parallel, with the drain connected to the LED. The light intensity is controlled by activating the appropriate number of transistors in the driver. The data received via the RF link are decoded by the communications control unit (CCU). The CMOS camera and the bidirectional RF link are controlled by the I2C control unit, which is a specifically-designed digital block dedicated to I2C communications. An additional S/A module can be switched to the capsule and controlled via the I2C bus (Figure 2). If the module is equipped with a motor controller, it is possible to perform drug delivery or biopsy. Specific devices have been created for this purpose.

## III. Results

Figure 5 shows the measured power consumption when performing the different tasks. It is clear that active functions require considerable power. Specific control of the power used at each instant is required so as not to exceed the maximum available energy, this task being performed by the microprocessor.

Table I summarises the main characteristics of the chip.




*Measurements have been done during the stationary phase.
Fig.5: Measured power consumption.

TABLE I
TABLE SUMMARIZING THE MAIN FEATURES OF THE SOC.

| | |
|---|---|
| TECHNOLOGY | 0.35UM HIGH VOLTAGE CMOS PROCESS OF AUSTRIAMICROSYSTEMS |
| SIZE | 5.1 mm X 5.2 mm |
| Nº OF EQUIVALENT GATES | 40 K |
| VOLTAGES | 3.3 V CORE<br>1.8 V INPUT OF CHARGE PUMP |
| POWER | 10 mW (IDLE MODE) |
| ANALOG MODULES | 2 3-PHASE INVERTERS<br>2 CHARGE PUMPS (5V)<br>6 LEVEL SHIFTERS (FROM 3.3 TO 5 V)<br>6 COMPARATORS<br>2 DAC (8-BIT)<br>1 HV H-BRIDGE<br>1 BOOST CONVERTER<br>2 HV LEVEL SHIFTERS (FROM 3.3 UP TO 50 V)<br>4 LEDS DRIVER |
| TRANSISTORS | 50 V HV-PMOS AND HV-NMOS (LENS DRIVER)<br>5 V PMOS AND NMOS (CHARGE PUMP AND LEVEL SHIFTERS)<br>3.3 V PMOS AND NMOS |
| MEMORY | 1 SRAM (8 KB)<br>1 SRAM (2 KB)<br>1 SRAM (256 B) |

*Measurements were made during the stationary phase.

## IV. INTEGRATION

Electronic devices, i.e. CMOS camera sensor, LEDs, RF transmitter, receiver and supply systems, and SoC, are placed inside the capsule using different boards for each device. The boards are circular and have a diameter of 10 mm. The circular shape is used so as to form the tubular space of the capsule.

For a basic configuration of the capsule five different boards are needed: one for LEDs and the CMOS camera sensor, one for the SoC, one for the RF transmitter, one for the sensors/actuators and one for the RF receiver and supply system. Each board is connected to the other boards and, if necessary, to other sensors/actuators (i.e. liquid lens, BLDC motors, etc.) through a FPC flat cable.

Figure 6 shows the complete system with five boards, sensors/actuators, electronic devices and the off-the-shelf components needed by the devices to work (e.g. the coils for the RF systems). Board number one includes the LEDs and the CMOS camera sensor in the top part, and some electronic components in the bottom part (e.g. the oscillator). The second board includes the SoC (the black resin) on one side and an EEPROM memory (needed to program the SoC) on the other. The third board includes some sensors and actuators, such as accelerometers, to calculate the position of the capsule. The fourth board includes the RF receiver system, the RF power source and the coil needed for that purpose. When the power consumption of the system is limited (i.e. the liquid lens and the motors are removed), the system can be powered using only the RF power source, without the need for a battery. Finally, the fifth board includes the RF transmitter system, used to send the acquired images to the doctors, and the coil needed for the transmitter.

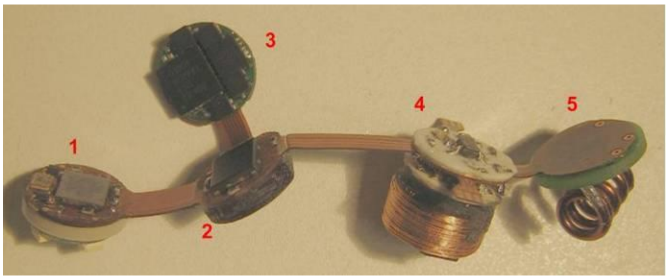


Fig.6: System Integration: electronics have been placed into 5 different boards.

## V. CONCLUSIONS

The next generation of endoscopic capsules needs to perform in vivo diagnosis and therapy. This paper has described the first SoC designed to control the functions of an endoscopic capsule with robotic capabilities. Instead of achieving control via multiple chips we have concentrated all the control electronics into a single chip which is able to generate the high current and high voltages required for today's actuators in microrobotics. This chip can be assembled in either a capsule or a conventional endoscope.

The paper has also shown how the SoC and the other electronic devices are placed in a real capsule endoscope. Here the diameter of the capsule is 10 mm. However, attempts should now be made to reduce the diameter of the boards in order to reduce the diameter of the capsule.

## ACKNOWLEDGMENT

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