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Control Electronics Integration toward Endoscopic Capsule Robot Performing Legged Locomotion and Illumination

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Abstract—**Miniaturization of sensors and actuators up to the point of active features in endoscopic capsules, such as locomotion or surgery, is a challenge. VECTOR endoscopic capsule has been designed to be the first endoscopic capsule with active locomotion. It is equipped with mini-legs driven by Brushless DC (BLDC) micro motors. In addition it can be also equipped with some other sensors and actuators, like a liquid lens, that permits to enable advanced functions. Those modules are managed by an ASIC specifically designed for the VECTOR capsule. The ASIC is a complete System-On-Chip (SoC) and integrates all the electronics needed to enable the legged locomotion and the sensing and actuating functions of the capsule in an unique chip. The SoC also enables other functions for endoscopic capsules such as drug delivery and a biopsy system. The size of the SoC is 5.1 mm x 5.2 mm in a 0.35 um high voltage CMOS technology.**

I. Introduction

THE significant development in medical diagnostics and imaging has brought up a lot of new wireless capsule camera products coming to health care market. The wireless capsule camera has been able to minimize patient discomfort and pain during digestive tract screening with less risk of infection and harmless to body organs. This kind of medical procedure is less invasive and gives a great impact compared to the traditional method.

The wireless capsule cameras are known by different names such as capsule camera, capsule endoscope, video pill, PillCam [1-2], EndoCapsule [3] or Sayaka [4]. Their shape look similar to a pill or capsule and they are able to see areas, which traditionally used endoscopes are unable to see. Wireless capsule camera also gives extra convenience to the patient. After swallowing one of the aforementioned capsules, patient may leave the hospital and return later after 8 hours. During this long period, the capsule captures images along the gastrointestinal (GI) tract while the patient is continuing the daily activity as normal.

Although pill-shaped micro-cameras have existed for over 9 years by now and are currently being used successfully in medical screening to study the GI tract, these systems are passive and are dependent to the peristaltic movement of the gastric wall to propel. The camera takes thousands of pictures as it passes through the GI tract, but its position during this time cannot be controlled. Therefore, many research institutions around the world are exploring the possibility to have an active endoscopic device for medical inspection and therapy in the form of capsular robot [5].

One of the biggest challenges facing the robotics scientists on developing robots relates to the extreme miniaturization of the electronic systems. The previous work by authors related to wireless control system [6] has been successfully tested in several active locomotion capsular robot prototypes, targeted for different areas of the GI tract; for example the swimming capsule [7] for large GI tract such as stomach and the legged capsule [8] for crawling through collapsed and folded tissue. However, those prototypes are rather big since extra sensors and actuators should be integrated in order to perform active locomotion. The capsule robot would even become slightly longer if we want to add additional auto-focus peripheral described in [9].

This paper describes how to integrate the electronics necessary to provide an endoscopic capsule with advanced functions mentioned. A vast amount of volume reduction of electronic control system has been achieved by integrating all actuator drivers, liquid lens driver and illumination driver in the form of a single die [10]. Thanks to the extra 8051 microcontroller within the Application Specific Integrated Circuit (ASIC), the motor speed can now be controlled easily, the illumination can be dimmed and the wireless controller can perform more intensive auto-focus algorithm aside from the communication to the surgeon. The ASIC preliminary testing presented in this paper was performed on the Versatile Endoscopic Capsule for Gastrointestinal Tumor Recognition and Therapy (VECTOR [11]) capsule, in particular the one with legged locomotion, controlling the legs motion and illumination.

II. State-of-Art

Several plausible works by scientists around the world in adding more features within a single die have been reported. The achievement is worth notice in term of system compactness and less power consumption. X. Xie et al. [12] proposed a particular Integrated Circuit (IC) architecture for this kind of endoscopic capsule. The system incorporates bidirectional communication, image compression and semi-active locomotion, allowing to control the capsule from outside. The locomotion system is built by a micro-current generator which electrodes are in contact with the GI wall.

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Applying electric current to the GI wall makes the surrounding muscle to contract, shrinking it and pushing the capsule forward. This feature is activated to skip uninteresting part during examination.

Another similar work in ASIC development was presented by X. Chen et al. [13]. This work also integrates bidirectional communication and image compression. Microcontroller with I2C bus is introduced within the system, enabling a full control over image sensor. In this way, the power consumption can be reduced by turning on/off the image sensor along uninteresting sites. Furthermore, the wireless wake-up feature can also be performed, saving even more power for later use.

III. The VECTOR Capsule

The architecture of the whole system is based on a System on Chip (SoC) as the central control unit, a CMOS camera, a bidirectional RF link and a group of peripherals. The complete system overview is depicted in figure 1. The I2C bus is present in the system for communication among different peripherals.

The control electronics have been fabricated in a unique chip. It includes an embedded 8051 microcontroller to control the entire system. It also contains all the electronics required to control active locomotion, illumination and focusing. The SoC is also able to manage via the I2C bus sensing and actuating platforms switched to the capsule to extend the functionalities or to provide specific functions in particular exploration scenarios.

The primary function of the VECTOR capsule is to acquire images of the GI tract in real time. For this reason the vision system of the VECTOR capsule is equipped with a monolithic 320×240 active-pixel RGB/gray level camera-on-a-chip sensor developed by Neuricam [14].

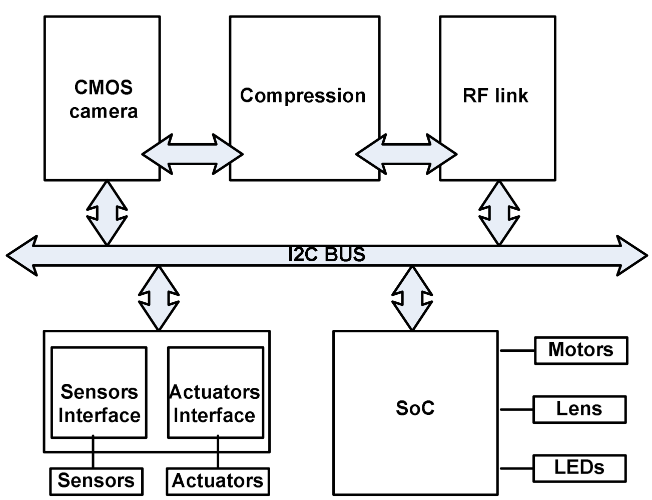

Figure 1: Internal architecture of the endoscopic capsule electronics.

The camera is connected to a compression chip that is in charge of reducing the data to be sent. Such data are sent directly to the exterior via the bidirectional RF link.

The illumination of the GI tract is done by using 4 groups of LEDs. As an advanced function, the vision system can be also equipped with a liquid lens (ARCTIC 416 liquid lens). The liquid lens has an electrically controllable focal length, bringing a novel idea of on-board auto-focus system for better image acquisitions [9].

The main advance in the VECTOR capsule is the inclusion of active locomotion. The VECTOR capsule is equipped with mini-legs. The motion of the legs is done by using two BLDC motors (by Namiki Precision Jewel Co).

Since VECTOR capsule is an active locomotion device for diagnostic and therapeutic purposes, it is also equipped with a group of selectable sensors and actuators. Particular sensors/actuators are mounted depending on diagnostic/therapeutic scheme instead of being always assembled due to space limitation. Examples of sensors/actuators are pH and tactile sensors, tissue sampling and drug delivery mechanisms.

The VECTOR capsule prototype is presented in figure 2. The size of the VECTOR capsule is 33 mm in length and 10 mm in diameter.

IV. ASIC description

Looking at the basic features implemented on the commercial capsule camera, it is a big challenge to keep these inherent features of the capsule camera and integrate additional and advanced capabilities on a robot capsule, such as active locomotion and an auto-focusing.

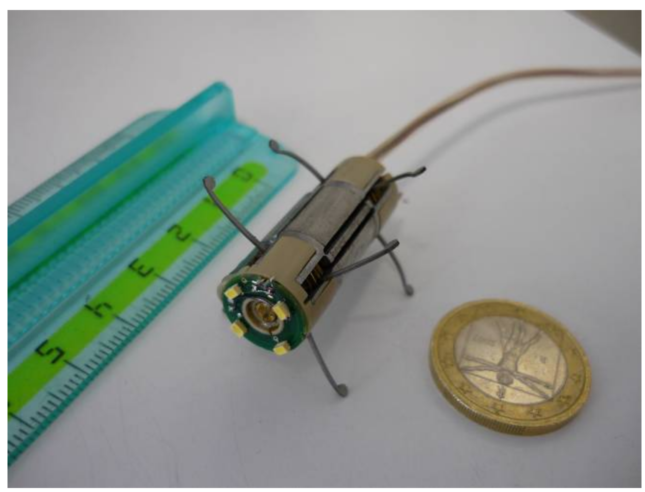

Figure 2: VECTOR capsule prototype equipped with 8 mini-legs and 4 white LEDs.

Beyond the trivial problems of integrating additional electronics on the same space, the difficulties arise to manage the actuators which enable the robotic functions. Driving of actuators require to manage high currents (up to a maximum of 100mA driving the motors) and high voltages (up to 50 V in the driving of the liquid lens). These drivers have to be integrated at the same time that the rest of the digital control electronics.

All the drivers and control electronics of the VECTOR capsule have been embedded in the same SoC fabricated with a 0.35 um HV CMOS technology. The technology use in the VECTOR capsule depends on the constraints imposed by the control of the liquid lens in the vision system. The liquid lens integrated in the capsule changes its focal length when a voltage in between 30 V and 50 V is applied.

Figure 3 shows the architecture of the SoC. The main block of the SoC is the embedded 8051 microprocessor which is the control unit (DW8051 IP). Specific peripherals have been included for each of the functions of the capsule. The peripherals determine the dynamic power consumption of the capsule. This strategy allows to administrate the instantaneous power to do not overpass the powering capabilities. The peripherals are the time stamp control unit (TSCU), the I2C control unit (I2CCU), the LEDs control unit (LCU), the lens control unit (LeCU), the clock generator unit (CGU), the communications control unit (CCU) and two locomotion control units (LoCU). Detailed description of the ASIC features is given next.

A. Main control description

The embedded 8051 microprocessor is in charge of executing the program uploaded in the program memory. The microprocessor has to configure all of control units as well. These are configured by accessing internal registers called Special Function Registers (SFR) by the DW8051 IP. The set of SFRs is defined by us as an internal bus. Therefore, the different blocks of the chip are controlled by accessing them through the internal bus.

The microprocessor is equipped with 256 B of SRAM internal memory, 2 kB SRAM of data memory and 8 kB SRAM of program memory. The memory type used is volatile. Therefore, each time the VECTOR capsule is up, the program has to be uploaded in the program memory area. EEPROM memories have not been selected because they are not available by the technology provider in the case of MPW projects and are not required at this stage of prototyping. The programming process is carried out by the Boot Loader (BL) that interprets and sends binary code received from serial port to particular program memory area. After the program is uploaded a Power On Reset is done to the processor and configuration registers.

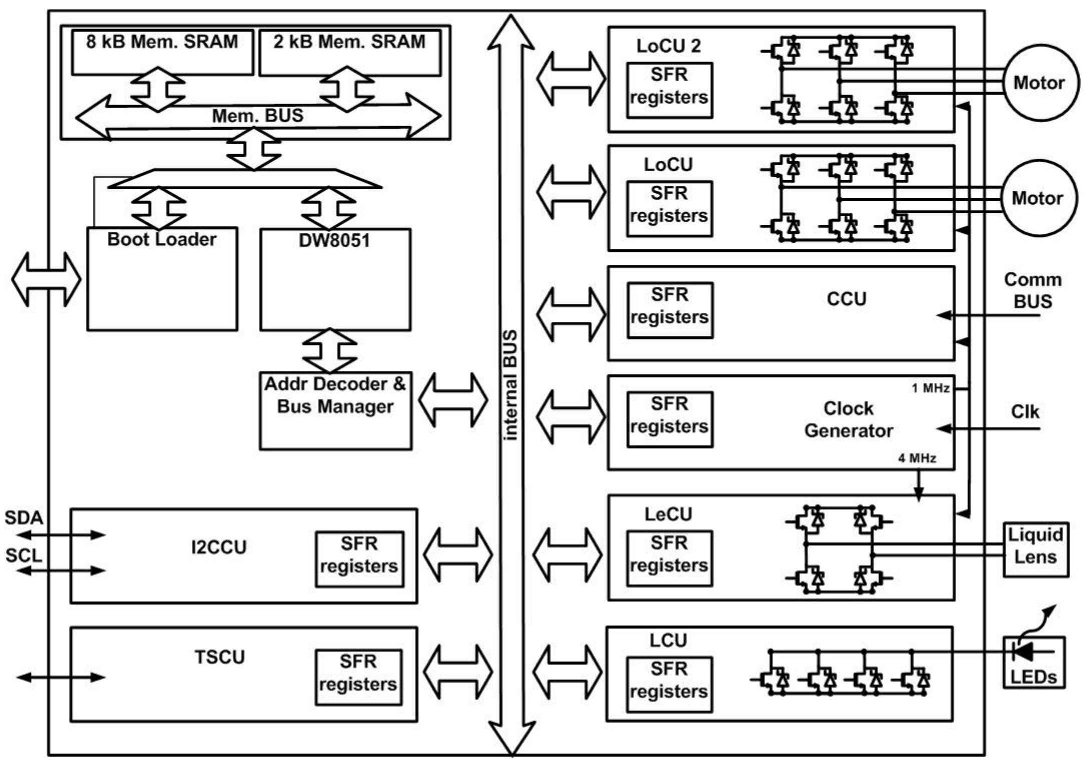

Figure 3: Architecture of the SoC.

The external clock required for this system to work properly is of 10 MHz. It is directly driven to the CGU. This unit is in charge of distributing the clock to all components of the system. In addition, the CGU also generates three extra clock signals: 4 MHz and 1 KHz for the LeCU and 1 MHz for the LoCU. These clocks are generated from the input main clock.

B. Advanced functions

As commented in previous sections, the most important advancement of the VECTOR capsule is active locomotion and real time video transmission. The locomotion of the robot is controlled by the LoCUs. They comprise a specific mixed-signal circuit with the digital part as the primary controller. To control the motors, the microprocessor configures the hardware block which generates particular driving signals for the motors. The hardware block is based on a finite state machine (FSM). This FSM is in charge of the start-up of the motors, and control the speed in the stationary regime using a sensorless control strategy. The analog part of the LoCU is the current driver.

Figure 4 presents the complete driver used for BLDC motors. As seen in the picture, the main part of the motor driver is the 3-phase structure. It is used to drive the motor. The 3-phase structure is only based on NMOS transistors, in order to have more robust latch-up. Six level shifters are used to drive the transistors of the 3-phase structure. The level-shifters increase the voltage range of the driving signals. Operating the transistors of the 3-phase inverter with 5 V gate voltage allows the use of smaller transistors compared with 3.3 V driving. The 5 V voltage can be generated by a Dickson charge pump, which is supplied by 1.8 V. It is preferable to increase the complexity of the electronics instead of using larger area for the driver. The sensorless BLDC motor control strategy is based on the measurement of the Back Electromotive Forces (BEMF) feedback generated at the motor coil. Thus, the motor driver is equipped with a feedback stage, composed by three comparators and a Digital to Analog Converter (DAC). Each comparator acquires BEMF signal from each motor phase and compares with the voltage reference generated by the DAC.

In normal operation, the LoCU is programmed with the start-up sequence, and configured to achieve the maximum speed possible. The start-up sequence consists of aligning the rotor to a known position and soon afterward commutating it in slow speed. This start-up sequence is necessary to generate BEMF feedback from the motor coil, because BEMF feedback can only be detected when the rotor turns. If everything goes well and the BEMF reading shows an adequate value, the next commutation should be triggered by the incoming BEMF signals. The proper BEMF reading can be achieved through skipping one electrical commutation ahead by 120 degree and waiting for the zero crossing on the respective floating coil.

Another advanced feature available in the VECTOR capsule is the auto-focus system. This is done using a liquid lens with the focal length changed when a voltage between 30 V and 50 V is applied to the lens electrodes.

The driving of the liquid lens is done by the LeCU. The LeCU is composed by a specific mixed-signal circuit with the digital part of the LeCU as the primary controller. The LeCU controller is based on an FSM as the one in charge of generating the lens driving signals. The analog part of the LeCU is the driver. Figure 6 illustrates the schematic of the driver. The main part of the lens driver is the H-Bridge (HB). It is composed by two HV-PMOS transistors, M1 and M2, which can afford a VDD of 50 V, and two HV-NMOS transistors, M3 and M4. The two outputs of the HB are connected directly to the liquid lens electrodes. The outputs are switched between 0V to 50 V, and the voltage across the liquid lens electrodes goes from -50 V to 50 V. The DC-DC Boost converter provide a supply voltage up to VDDH = 50 V, which is used to power the H-Bridge and two High Voltage level-shifters. The boost converter is powered by 3.3 V supply. The High Voltage level-shifters are needed to raise the driving signals to the operating gate voltages of the HV-PMOS transistors. Thus, the pMOS transistors of the HB are driven with signal from VDDH to VDDH – 2 VTHP (where VTHP is the threshold voltage of the PMOS transistor). Two more additional level-shifters biased with 5 V supply are connected directly to the gates of the two HV-NMOS transistors, M3 and M4, of the HB. A charge pump, based on the Dickson charge pump, generates the 5 V supply signal.

In normal operation, the LeCU is programmed to manipulate the liquid lens focal length. Basically, by changing the frequency of the boost converter control signal, the voltage supply is changed between 30 V and 50 V. The lens convexity is almost proportional to the voltage applied.

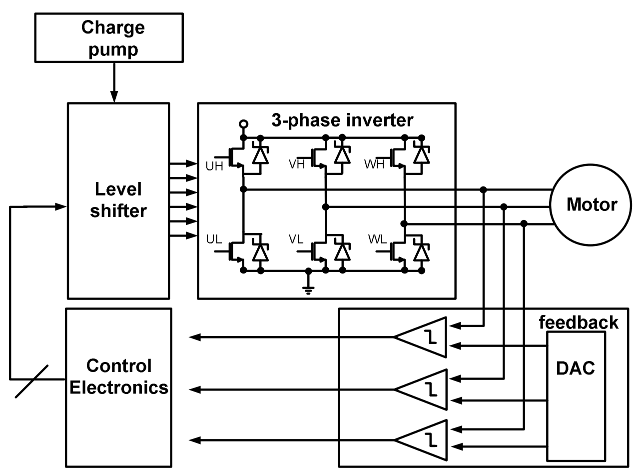

Figure 4: Internal architecture of the endoscopic capsule electronics.

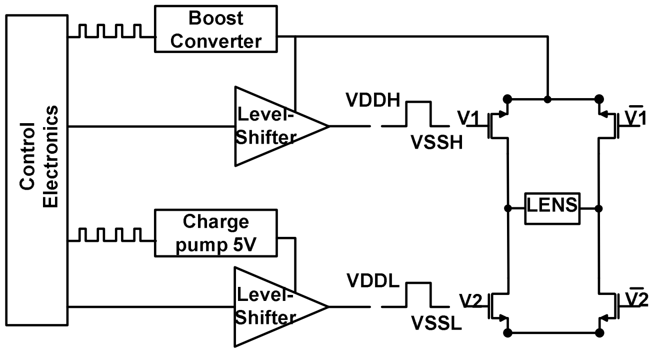

Figure 5: Simplified schematic of the lens driver.

C. *Basic functions*

It is mandatory in an endoscopic capsule to have the possibility to take images and send the information outside the body. The image sensor of the VECTOR capsule is controlled via the I2CCU. The I2CCU is a specially designed digital block devoted to the I2C communications. The I2C bus connects the Sensor/Actuator interface, the camera, the RF link and the SoC. In the case of the VECTOR capsule, the SoC is the Master of the I2C bus.

The I2CCU provides I2C control signal to the camera while the TSCU generates a synchronization signal. Once the camera is started, the images acquired by the CMOS sensor are sent to a compressor unit. The compressed images are then sent, together with the synchronization signal from TSCU, to a bidirectional RF link, which sends them outside to the receiver unit. It is worth to notice that both compressor and RF link are not parts of SoC.

As a bidirectional link, the RF link can also receive data. These data are sent to the microprocessor via the serial communication input. The working frequency of the serial input is 4.8 kHz. The I2CCU is responsible of decoding and sending an interruption to the microprocessor when valid data have been received. These data are stored into the SFRs. Once the microprocessor receives the interruption, it stops its activity, reads and executes the received data. The I2CCU provides the medical doctor a full control over the camera feature. The doctors can start/stop any activity of the capsule, or even re-program the capsule from outside.

The illumination of the GI tract is done by using LEDs. The LEDs are turned on/off by the LCU. The SFRs of the LCU are directly connected to the LEDs driver (Figure 8). The SFRs are configured by the microprocessor. The LEDs driver is composed of 8 transistors in parallel, with the Drain pins connected to the LED. Each transistor has a different W/L ratio. With this strategy, it is possible to control the current passes through the LED controlling the intensity of LEDs.

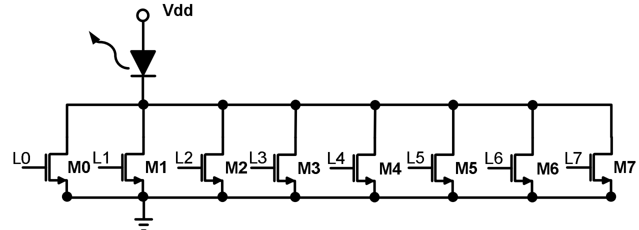

Figure 6: Simplified schematic of the lens driver.

D. *Operating system*

All the system is controlled by a real time operating system (RTOS). The core software is based on the RTX51 by Keil. Basically, the RTOS distributes different operations to be done in the form of tasks. Within the RTOS, all of these tasks seem to run simultaneously and the program will be executed once the complete code is received by microcontroller through the serial communication. Since the system is divided into several hardware control units, it is easier to perform each task control over each hardware block.

V. Implementation results

The die photo is shown in figure 7. The size of the SoC is 5.1 mm x 5.2 mm. The SoC is able to generate voltage signals of 5 V and up to 50 V, by using 2 externals capacitors of 36 nF and 300 nF, and an external inductor of 220 uH.

The test of the ASIC has been performed using a wired VECTOR capsule prototype equipped with 8 mini-legs and 4 white LEDs. The procedure for testing was straightforward on an experimental board comprising one microcontroller and the ASIC. The microcontroller (PIC18F2550) is used to configure the ASIC each time we want to experiment with new programs. On the test bench, three connectors for BLDC motors and LEDs are connected to the ASIC.

A graphical user interface (GUI) application written in JAVA language has been developed to communicate with the PIC18F2500 through USB port. Figure 8 shows the VECTOR capsule prototype connected to the experimental board. In the accompanying video it is shown how the capsule opens and closes the legs while the illumination is turned on and off simultaneously.

The wired capsule prototype allows us to measure the power consumption. Table I presents the measured power consumption of each task performed by the VECTOR capsule prototype. The tasks are enabled/disabled by the microprocessor. The maximum power demand is in the locomotion module. Each BLDC motor is connected to 4 legs. Therefore, it is possible to move 4 or 8 legs. The power consumption of the motor during the start-up is higher than in the stationary. However, the start-up does not alter the behavior of the VECTOR capsule because it is done in a short time (i.e. 10 ms).

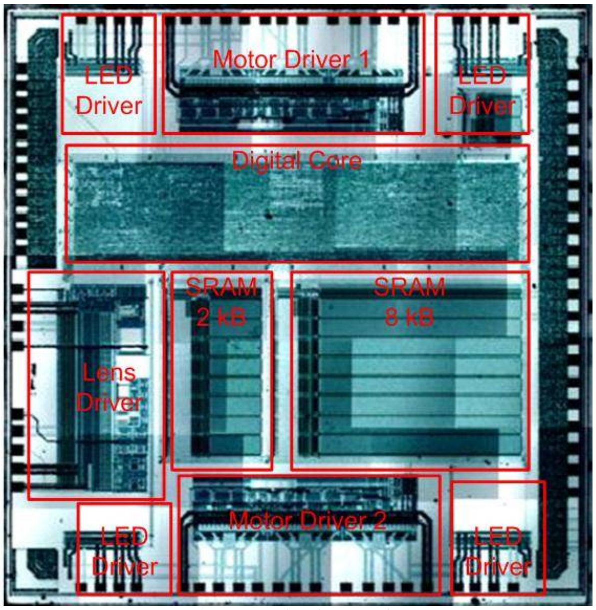

Figure 7: Die photografy.

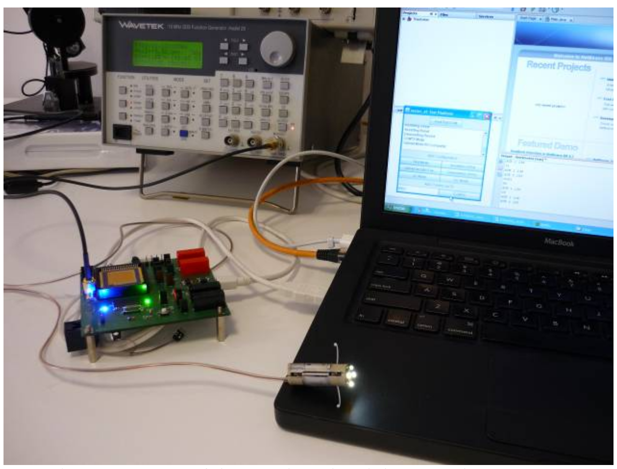

Figure 8: Image of the Test board and the Capsule prototype.

TABLE I
POWER CONSUMPTION OF BASIC TASKS @10MHZ

Module	Task	Power (mW)
uP	IDLE	7,2
	Move Motor 1	174,9*
LoCU	Move Motor 2	174,9*
LeCU	Lens focusing @ 50 V	88 ,0
LCU	4 LEDs	70,3
I2CCU	Communicating with an slave	< 3

*Measurements have been done during the stationary phase.

VI. CONCLUSIONS

The next generation of endoscopic capsules needs to perform in vivo diagnosis and therapy. In this work we describe the first SoC that has been designed to control the functions of an endoscopic capsule with robotic capabilities. Instead of using multiple chips, we have concentrated all the control electronics in a unique chip which is able to generate high current and high voltages required for today actuators in microrobotics. It can be assembled in a capsule of in a conventional endoscope.

In addition, locomotion and the innovative vision system improve the medical diagnosis because the doctors have a total control of the endoscopic robot. This provides better accuracy during the exploration because the capsule robot is able to approach and focus over the desired section of the GI tract. Furthermore, thanks to the active locomotion, it is possible to do a faster exploration, compared with existing solutions. It permits to exclude the heal area and a faster approaching to the diseased area.

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