Enabling active locomotion and advanced features in capsule endoscopy

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Enabling active locomotion and advanced features in an endoscopic capsule

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Preface and Organization

The significant development in medical diagnostics and imaging has brought up a lot of new wireless capsule endoscopes coming to health care market. The capsule 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.

Although pill-shaped capsules have existed for over 11 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 aim of this work is to provide the electronics needed to control an endoscopic capsule robot and the electronics needed to enable active locomotion and advanced vision functions (like autofocus). Enabling such functions the capsules will be able to perform screening, diagnosis and therapy. Such capsule robot has been designed in the framework of the "Versatile Endoscopic Capsule for Gastrointestinal Tumour Recognition and Therapy" (VECTOR) project. This project pursues the goal of realizing smart pill technologies and applications for gastrointestinal (GI) diagnosis and therapy. The overall medical goal of the project is to enable medical devices through advanced technology that can dramatically improve early detection and treatment of GI early cancers and cancer precursors. The main technological objective of the project is the take-up of microsystems and sub-components and their integration into robotic, mobile pill devices for useful and large impact applications in the medical field.

The current work is structured as follows. In Chapter 1, it is described the use of actual medical robots and how medicine could be improved by using miniaturized robots. In particular, a description of the main GI diseases and GI exploration methods is presented in order to understand how capsular endoscopy can help to improve the diagnosis and the therapy in this particular region.

Two different solutions to improve capsular endoscopy are presented in Chapter 2. The first solution consists in having a capsular endoscope microrobot equipped with several sensors and actuators in order to enable as much functions as possible (i.e. active locomotion, autofocus, therapy …). The second solution consists in splitting the microrobotic solution into 3 different capsules, each one designed specifically for one function: screening, diagnosis and therapy. The electronics needed to enable each solution are integrated in two different ASICs (one for each solution)

In Chapter 3 it is given in detail the design process to enable active locomotion in capsular endoscopy. From the election of the type of locomotion to the design of the electronics needed to enable the movement. In particular, the space constraints imposed by the small size of the capsule requires a high effort to reduce the size of the electronics as much as possible.

In Chapter 4, the electronics needed to drive a liquid lens are presented. The liquid lens permits to enable advanced vision functions like the autofocus function or the zoom function. The inclusion of this actuator and its electronics in a capsular endoscope permits to use capsules to examine the entire GI tract because it is possible to acquire focused images of each region.

A practical implementation of the ASIC in a capsule can be found in Chapter 5. In this chapter, the ASIC designed and presented in Chapter 2 is used to enable therapy in a capsule. In particular, the capsule is capable of clipping lesions to stop bleedings in the colon. Such capsule is equipped with an energy scavenging consisting in an inductive power link.

Finally, in Chapter 6 are presented the conclusions of this work.

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1.Introduction

Cancers of the digestive tract are among the most significant killers in developed countries, with colon cancer ranging among the top 10 causes of death for both genders, male and female. If the disease is detected at the stage of pre-malignancy, local therapy, such as tissue resection or destruction, can be used to eradicate the disease before malignant transformation and the onset of invasive cancer.

In recent years, the robotics technology has evolved enough to be applied in medicine in a safety way. Nowadays it is possible to find robots which are used to help the doctors in many ways (i.e. in surgery, drug delivery ...). Such robots improve the actual diagnostic and therapy systems because they are more precise and make fewer mistakes than doctors. In addition, the advances done in Micro-Electro-Mechanical Systems (MEMS) permits to miniaturize these robots, to use them in a less invasive way and to use the robots inside the human body due to its small size. This thesis focuses on the design of the control electronics for one of these robots, who will be used to diagnose cancer and to perform therapy in the digestive tract.

In this introduction, the use of medical robots and the need of miniaturization are presented in Section 1.1. Different diseases and exploration methods of the Gastro intestinal (GI) tract are presented in Section 1.2 in order to know what kind of actions must be performed by a miniaturized robot placed in the GI tract. Capsular endoscopy is detailed in Section 1.3.

1.1. Medical robots

In the year 2010, a surgical operation completely performed by robots was realized for first time. The intervention was made possible thanks to the Da Vinci robot (made by Intuitive Surgical [1], which allows doctors to perform operations from remote sites, and McSleepy, an android that since 2008 is responsible for automated anesthesia in operating rooms. Both robots were used to remove the prostate of a patient at the Montreal General Hospital.

In medicine, robots can perform tasks with greater accuracy and safety, creating better results. In this field the Da Vinci robot is the benchmark, because it is capable of performing highly accurate precision movements that would not be possible to achieve without him.

Robotics has revolutionized the field of medicine and currently has several applications in the service of health. Although many of these applications are still under test and research, many others are already used around the world with very satisfactory results. Some applications of robotics in medicine include:

- Robot-prosthesis: Intelligent prostheses have been used for several years, allowing the replacement of damaged parts of the musculoskeletal system.

- Exoskeletons and active orthoses: They are advanced bionic devices that are attached to the body to improve and enhance the capabilities of it. They are also called "robotic clothes" and they benefit people with disabilities, helping them to improve their quality of life and displacement.

- Therapeutic Robotics: It is used in hospital or at home to provide an accelerated rehabilitation to patients who have suffered illness or accidents that have reduced their motor functions. The field of rehabilitation robotics includes artificial limbs, robots for rehabilitation therapy support or providing personal assistance robots in hospitals.

However, the most important advance in medicine due to robotics is the Robotic surgery. Robotics has been transforming the conventional surgical practices, reducing the margin of error in the response.

The idea of using robots in the field of surgery was born many years ago in the U.S. Department of Defense, which sought to develop machines that could transmit distance movements and knowledge for use in the battlefield. Nowadays, robotic surgery is a reality that allows the physician to operate from the next room or being at many miles from the patient.

Robotic surgery offers to patients many benefits, including a shorter hospital stay, less pain, smaller scars, less blood loss, fewer transfusions, less risk of infection or faster recovery [2,3]. Robotics allows surgeons a greater precision in the interventions and allows them to explore the surgical field with the aid of a magnification similar to that found in microsurgery.

The history of surgical robots is recent. One of the first prototypes of surgical robots was Minerva [4,5], built in 1991. It was designed for interventions of neurosurgery. Also in 1991 was presented Robodoc [6], a robot that used the information from scans in the femoral prosthesis implant.

In 1993, the AESOP robot 1000 (Advanced Endoscopic System for Optimal Positioning) became the first assistant surgeon [7], because it was used to drive a laparoscope cholecystectomy. In the same year appeared ESOPO, a slave robot which is controlled by voice commands from the surgeon. In addition, the surgeon was also able to control the operating room (surgical table lamps and laparoscopy equipment) as well as the ability to communicate via telephone and internet with voice commands. This integration of technology was named the Intelligent Operating Room.

Finally, the da Vinci system was approved in the year 2000, and nowadays there are more than 1000 da Vinci robots sold around the world [8]. The system is controlled by a surgeon from a console. The da Vinci robot is mostly used for prostatectomies, cardiac valve repair and gynecologic surgical procedures [9-11].

Thanks to their benefits, nowadays surgical robots are widely used around the world. Nevertheless the trend is to miniaturize the system. Due to their size, surgical robots operate from outside to inside the human body. However, using small robots it could be possible to operate from inside the human body, attacking from inside the region under study and, possibly, avoiding the need of surgery for the patient. Furthermore, the use of these microrobots results in even less trauma to the patient, faster recovery times and, in addition, it also enables new therapies.

Due to its shape and size (minimum diameter approximately 3 cm), the GI tract is the most desirable human region to work with the first miniaturized medical robots. In order to understand the needs and functions for the miniaturized medical robots in the GI tract, it is needed to meet the fields of medicine and microrobotics. In particular, it is needed to understand what are the main diseases that can affect the GI tract, what are the existing techniques used by the doctors to explore and detect diseases in the GI tract and how can the robots be miniaturized.

1.2. Miniaturizing medical robots

Miniaturized robotic systems open new challenges not only in surgical robotics but also in many related areas such as sensor systems, locomotion, energy supplying, communications and so on [12] due to its small size. Nevertheless, miniaturization of medical robots for the GI tract is even more difficult, because the GI tract presents too many diseases with different symptoms which require the use of several techniques to explore, analyse and diagnose the GI tract. Therefore, building a microrobot capable of covering all these medical needs is a big challenge.

In order to understand the medical needs this section presents the main GI diseases, exploration and imaging techniques. Furthermore, it also includes a sub-section devoted to microrobotics in order to understand the limits and capabilities of robotic miniaturization.

1.2.1. GI diseases

There are lots of different diseases that can affect the GI tract. The aim of this section is to present disease definitions, cancers and pre-malignant lesions that require especial interventions from the doctors in order to diagnose and treat such diseases. The more important GI diseases, taking into account their incidence and the mortality risk are [13]:

- Esophageal cancer: Cancer that forms in tissues lining the esophagus.

- Stomach cancer: Cancer that forms in tissues lining the stomach. Also called gastric cancer. Chronic inflammation with gastric atrophy was shown to be the most important pathological entity.

- Gastro-esophageal reflux: Gastro-esophageal reflux disease (GERD) is to be shared to gastroesophageal reflux (GER). GER is also called acid reflux or acid regurgitation

Occasional GER is common and does not necessarily mean one has GERD. Persistent reflux that occurs more than twice a week is considered GERD, and it can eventually lead to more serious health problems. The main symptom of GERD in adults is frequent heartburn.

- Barrett's esophagus: Barrett’s esophagus is a condition in which the tissue lining the esophagus is replaced by tissue that is similar to the lining of the intestine. This process is called intestinal metaplasia.

- Colon polyps: A colon polyp is a growth on the surface of the colon, also called the large intestine. Sometimes, a person can have more than one colon polyp. Colon polyps can be raised or flat.

- Obscure bleeding: Bleeding in the digestive tract is a symptom of a disease rather than a disease itself. A number of different conditions can cause bleeding. Most causes of bleeding are related to conditions that can be cured or controlled, such as ulcers or hemorrhoids. Some causes of bleeding may be life threatening.

- Colorectal cancer: Cancer that forms in the tissues of the colon (the longest part of the large intestine) or in the tissues of the rectum (the last several inches of the large intestine closest to the anus).

- Crohn’s disease: Crohn’s disease may also be called ileitis or enteritis. Crohn’s disease is an ongoing disorder that causes inflammation of the GI tract. Crohn’s disease can affect any area of the GI tract, from the mouth to the anus, but it most commonly affects the lower part of the small

intestine, called the ileum. The swelling extends deep into the lining of the affected organ. The swelling can cause pain and can make the intestines empty frequently, resulting in diarrhea.

- Celiac disease: Celiac disease is a digestive disease that damages the small intestine and interferes with absorption of nutrients from food. People who have celiac disease cannot tolerate gluten, a protein in wheat, rye, and barley. Gluten is found mainly in foods but may also be found in everyday products such as medicines, vitamins, and lip balms. Table 1.1 summarises the symptoms/risks and the incidence of each of these diseases.

Table 1.1: Symptoms/risks and incidence of some of the most dangerous diseases of the GI tract.

			R
Esophageal cancer	I	In 2010, in the United States, appeared 16,640 new cases of oesophageal cancers and there were 14,500 deaths due to this type of cancer.	[13, Chapter 5]
	S/R	It is uncertain which risk factors contribute to the increasing incidence of esophageal adenocarcinoma, although gastroesophageal reflux disease, cigarette smoking, and obesity have been implicated.	
Stomach cancer	I	Despite declining incidence still remains the second cause of death of all malignancies worldwide. In 2010, in the United States, appeared 21,000 new cases of gastric cancers and there were 10,570 deaths due to this type of cancer.	[13, Chapter 6]
	S/R	Diets riches of salts and nitrates, alcohol, smoking are involved in initiation and progression of this cancer. In the other side an increased consumption of food containing natural antioxidants such as fresh fruit and vegetables may slow or prevent the disease.	
Gastro-esophageal reflux	I	The overall incidence of GERD was 307 per 100,000 population/year.	[14-17]
	S/R	The reason some people develop GERD is still unclear. However, research shows that in people with GERD, the lower esophageal sphincter (LES) relaxes while the rest of the esophagus is working. Anatomical abnormalities such as a hiatal hernia may also contribute to GERD.	
Barrett's esophagus	I	Barrett's esophagus affects about 1% of adults in the United States. The average age at diagnosis is 50, but determining when the problem started is usually difficult. Men develop Barrett's esophagus twice as often as women, and Caucasian men are affected more frequently than men of other races. Barrett's esophagus is uncommon in children.	[18,19]
	S/R	While Barrett's esophagus may cause no symptoms itself, a small number of people (less than 1%) with this condition develop a relatively rare but often deadly type of cancer of the esophagus.	
Colon polyps	I	Population and autopsy studies suggest that about 30% of middle-aged or elderly individuals have colonic polyps.	[20]
	S/R	Most people with colon polyps do not have symptoms. Often, people don't know they have one until the doctor finds it during a regular checkup or while testing for something else. But some people do have symptoms, such as bleeding from the anus, constipation or diarrhea that lasts more than a week or blood in the stool.	

Obscure bleeding	I	It is a very common disease worldwide, although data on the exact prevalence are not available. Given that most people are not tested for Obscure bleeding, the incidence of occult bleeding is almost certainly underestimated.	[21-23]
	S/R	It is extremely common and can be caused by virtually any lesion in the gastrointestinal tract.	
Colorectal cancer	I	Colorectal cancers (CRC) are the second leading cause of cancer related deaths in the United States. Each year approximately 140.000 individuals are diagnosed with CRC and more than 50.000 die from this group of diseases. Incidence and mortality of colon cancer can be effectively lowered by population screening. The individual risk status of the patients has to be assessed before the screening procedure.	[24-32]
	S/R	There are important evidences that lifestyle factors influence the development of this malignancy. Although the precise mechanisms have not been clarified, several lifestyle factors are likely to have a major impact on colorectal cancer development. Physical inactivity and to a lesser extent, excess body weight, are consistent risk factors for colon cancer. Exposure to tobacco products early in life is also associated with a higher risk of developing colorectal neoplasia. Diets containing high amounts of red and processed meat increase the risk. Excessive alcohol consumption, probably in combination with a diet low in micronutrients such as folic acid and methionine, appear to increase risk as well.	
Crohn's disease	I	Crohn's disease affects men and women equally and seems to run in some families. About 7 of every 100,000 people in USA have Crohn's disease. These are among the highest rates in the world. The incidence is about 1-3 per 100,000 in southern Europe, South Africa, and Australia, and is even lower, less than 1 per 100,000, in Asia and South America.	[33]
	S/R	The most common symptoms of Crohn's disease are abdominal pain, often in the lower right area, and diarrhea. Rectal bleeding, weight loss, arthritis, skin problems, and fever may also occur. Bleeding may be serious and persistent, leading to anemia. Children with Crohn's disease may suffer delayed development and stunted growth. The range and severity of symptoms varies.	
Celiac disease	I	Originally thought to be a rare childhood syndrome, celiac disease is now known to be a common genetic disorder. More than 2 million people in the United States have the disease, or about 1 in 133 people. Among people who have a first-degree relative (a parent, sibling, or child) diagnosed with celiac disease, as many as 1 in 22 people may have the disease. Celiac disease is also more common among people with other genetic disorders including Down syndrome and Turner syndrome, a condition that affects girls' development.	[34]
	S/R	Symptoms of celiac disease vary from person to person. Symptoms may occur in the digestive system or in other parts of the body. Digestive symptoms are more common in infants and young children and may include abdominal bloating and pain, chronic diarrhea, vomiting, constipation, pale, foul-smelling, or fatty stool and weight loss.	

I is the abbreviation of Incidence, S/R is the abbreviation of Symptoms/Risks and R is the abbreviation of References.

1.2.2. GI exploration techniques

In the previous section it has been presented some dangerous diseases that may affect the GI tract. The detection and diagnosis of these diseases is difficult because it cannot be analyzed by examining the GI tract, due to its length and the fact that it is located inside the human body. The method used by doctors when analyzing the GI tract is endoscopy. Basically, the endoscopy consists in introducing, inside the GI tract, a thin tube with a video camera and light at the tip. The basic function of this system is to show to doctors the GI tract without any need of surgery. The tube can be inserted both orally and rectally. Endoscopy in the digestive tract is named differently depending on the area under study and the applied techniques, the procedures most widely used are esofagogastruoduedonoscopy (EGD), double ballon enteroscopy, push enteroscopy, colonoscopy and flexible sigmoidescopy (FS). These exploration techniques are summarized in Table 1.2.

Although conventional endoscopy allows examining the digestive tract, it also has some disadvantages. For example, endoscopy is not a comfortable treatment for the patient because it requires the introduction of a tube inside the human body. Furthermore, endoscopy cannot access the entire GI tract. For example, doctors are only able to study a small part of the small bowel. Conventional endoscopy is not always effective, as the conditions are so adverse in the GI tract (long extension, folds of tissue, poor lighting) that the doctor is not always able to detect diseases, which requires a second endoscopy or some alternative method. Other drawbacks are the risk of infection, the risk of bowel perforation or the need to use anaesthesia in some cases. Finally, endoscopy has to be practiced in a hospital, which means that it is not usually done in small towns.

The need to improve the existing method and the fact that the number of people around the world that access to endoscopy is about 15 million per year [44] has led to the emergence of alternative methods such as upper GI series, urea breath test, trans abdominal ultrasonography, esophageal gastric PH and bile monitoring, fecal occult blood test (FOBT), virtual colonoscopy and capsule endoscopy. These alternative exploration techniques are summarized in Table 1.3. These methods are often used to complement traditional endoscopy, although in certain cases (e.g. patients who cannot access traditional endoscopy for physical reasons) can be used to diagnose.

Nevertheless, the health industry, patients and doctors have accepted that the future of endoscopy is capsular endoscopy:

- It performs better diagnosis because it can diagnose the entire GI tract.
- It is confortable for the patients because it causes less pain due to its small size.
- It is capable to include more functions than diagnosis, for example it will be capable of performing therapy or drug delivery in a near future. Such capabilities are only available in actual endoscopes at this moment.
- It is disposable, which eliminates any possibility of in-hospital infection that can be associated with conventional endoscopy.
- It reduces the risk of bowel perforation.

1.2.3. GI imaging techniques

The endoscope is one of the medical tools more used to examine the GI tract. An endoscope usually consists of a rigid or flexible tube, a light delivery system to illuminate the organ or object under inspection (the light source is normally outside the body and the light is typically directed via an optical fiber system), a lens system transmitting the image to the viewer from the objective lens to the viewer (placed at the end of the tube), an eyepiece and an additional channel to allow entry of medical instruments or manipulators. The analysis of the GI tract is done by visually examining the images

acquired by the endoscope. These images are shown in real time (i.e. 25 frames per second) in a monitor. Nowadays, it is possible to find endoscopes capable to show the images in HD quality in an HD monitor [61].

One possible way to improve such procedure is improving/adding other imaging techniques, which can be combined with endoscopy. These imaging techniques are endoscopic ultrasounds (EUS), narrow band imaging (NBI), chromoendoscopy, magnifying endoscopy and fluorescence endoscopy. Further details of these imaging techniques are given in Table 1.4.

Table 1.2: Some exploration techniques applied in the GI tract.

		R
EGD	Includes the study of the oesophagus, stomach and duodenum. This procedure is used to discover the reason for swallowing difficulties, nausea, vomiting, reflux, bleeding, indigestion, abdominal pain, or chest pain. In particular, for this procedure the endoscope can be introduced through the nose or the mouth of the patients, who have been previously sedated in order to reduce the pain during the examination. In addition, the scope also blows air into the stomach in order to expand the folds of tissue and give the possibility of look through the folders.	[35]
Double Balloon Enteroscopy	It is used to study the small bowel. It is a newly developed endoscopic method which permits to explore the small bowel without any need of surgical intervention. Using a simple push and pull method two balloons are used in this procedure to examine the small intestine in steps approximately 40 cm long. Double balloon endoscopy is indicated in cases of unclear bleeding in the digestive tract, Chron's disease, unclear chronic diarrhoea, abdominal pain, intestinal polyposis, intestinal dysplasia and Celiac disease.	[36,37]
Push Enteroscopy	It is also used for the study of the small bowel. During this procedure, a long, narrow, flexible gastrointestinal endoscope, known as a push enteroscope, is advanced into the upper gastrointestinal tract to examine and evaluate the proximal section (first one third) of the small bowel. This procedure is indicated when the doctors are not able to identify the cause of obscure bleeding or some other GI disorder.	[38]
Colonoscopy	The colonoscopy is the less invasive technique that uses a scope to examine the colon and the distal part of the small bowel. Although colonoscopy is a safe procedure, complications can sometimes occur. These include perforation a puncture of the colon walls, which could require surgical repair. Sedation during the examination, post-procedural abdominal pain and irritable bowel syndrome are the main drawbacks. However, with this procedure biopsies can be taken of any abnormal areas at the same time as the screening or diagnostic test is being done. Any polyps found can be removed during this procedure	[39-43]
Flexible Sigmoidescopy	It is similar to the colonoscopy. However, this procedure only examines the region from the rectum to the colon (also known as sigmoid). This procedure is one of the screening modalities for colorectal cancer. From the point of view of screening, FS clearly cannot completely exclude the presence of colon cancer in all asymptomatic people. However, FS every 5 years with or without FOBT is one of the screening methods recommended by major professional organizations. It identifies 50 to 70% of the advanced neoplasms.	[45,46]

R is the abbreviation of References.

Table 1.3: Alternative exploration techniques applied in the GI tract.

		R
Upper GI series	X-rays are used to diagnose problems in the oesophagus, stomach and duodenum, but also could serve to diagnose the small fine. In order to diagnose using X-rays, the patient has to drink a barium solution before the procedure. The barium solution shows up more clearly the regions under study on X-rays. With this procedure the doctors can detect ulcers, scar tissue, abnormal growths, hernias or areas where something is blocking the normal path of food. The main disadvantage for the patients is that barium may cause constipation and white-coloured stool for a few days after the procedure.	[47,48]
Urea Breath Test	It is based on the ability of Helicobacter pylori to break down urea, a chemical made up of nitrogen and carbon. The H. Pylori is a spiral bacterium implicated in gastritis, gastric ulcer, and peptic ulcer disease. Urea breath tests are recommended in leading society guidelines as a preferred non-invasive choice for detecting H. pylori before and after treatment.	[49,50]
Trans Abdominal Ultrasonography	Ultrasonography represents a simple and well-tolerated diagnostic approach in sliding gastric hiatal hernia. Oesophageal diameter was measured by ultrasonography at the level of the diaphragmatic hiatus. The good diagnostic accuracy suggests its potential use in clinical and epidemiological settings.	[51]
Oesophageal Gastric PH and Bile Monitoring	It consist in inserting a small tube into the oesophagus or clipping a tiny device to the oesophagus that will stay there for 24 to 48 hours, this technique could be performed with a transnasally approach. Once introduced, the patient is able to perform normal activities while the device measures how much acid comes up into the oesophagus.	[52]
Fecal Occult Blood Test	Two samples from each of 3 consecutive stools should be tested. Patients with positive FOBT results are at increased risk of advanced neoplasia and should undergo a complete colonoscopy. Several randomized studies have shown that colorectal cancer (CRC) screening by FOBT reduces their mortality. These trials have different designs, especially concerning FOBT frequency and duration, as well as the length of follow-up after stopping FOBT campaigns. Biennial FOBT decreased CRC mortality by 14% when performed over 10 years.	[53-55]
Virtual Colonoscopy	The procedure is used to diagnose colon and bowel disease, including polyps, diverticulitis, and cancer. Virtual colonoscopy uses X-rays and computers to generate a 2-D or 3-D image of the colon. However, this procedure also requires the introduction of a thin tube in the rectum which pumps air in order to inflate the colon for better viewing.	[56-58]
Capsular Endoscopy	It is a minimally invasive procedure that permits to study the whole GI tract. Capsular endoscopy consists in a small capsule with the shape of a pill, which contains some electronics elements needed to perform the same task as the traditional endoscopy. Such electronic elements are basically a tiny camera, some LEDs for the illumination of the GI tract, a radiofrequency (RF) system needed to transmit the acquired images to the doctors and a battery (needed to supply the capsule).	[59,60]

R is the abbreviation of References.

Table 1.4: Imaging techniques applied in the GI tract.

		R
EUS	EUS combines endoscopy and ultrasound in order to obtain images and information about the digestive tract and the surrounding tissue and organs. Ultrasound uses high-frequency sound waves to produce images of the organs and structures inside the body such as ovaries, uterus, liver, gallbladder, pancreas, aorta, etc. EUS uses a small ultrasound transducer installed on the tip of the endoscope.	[62]
NBI	NBI may enhance the accuracy of diagnosis by using narrow-bandwidth filters in a red-green-blue (R/G/B) sequential illumination system. This results in different images at distinct levels of the mucosa and increases the contrast between the epithelial surface and the subjacent vascular pattern.	[63,64]
Chromoendoscopy	It involves the topical application of stains or pigments to improve tissue localization, characterization, or diagnosis during endoscopy. Reactive stains (e.g., Congo red and phenol red) undergo chemical reactions with specific cellular constituents, resulting in a color change. The stains used for chromoendoscopy are transient, unlike the stains used to tattoo lesions.	[65]
Magnifying endoscopy	It enhances the visualization of mucosal details by enlarging the image. Magnifying endoscopes have an optical zooming mechanism composed of a movable motor-driven lens in the tip of the scope. By controlling the focal distance, the scope can approach the mucosal surface extremely closely, thereby providing a magnified image of up to 200x. The resulting image produces detailed visualization of the fine structures of the mucosa.	[50-54]
Fluorescence endoscopy	It uses fluorescein-labelled chemicals either sprayed on the lining of the GI tract or injected intravenously. The chemicals are taken up by abnormal cells (premalignant and malignant) of the lining of the GI tract more than the normal cells, and special lighting make the areas of abnormal cells clearer to see so they can be biopsied or removed completely.	

R is the abbreviation of References.

The main characteristic of these functions is that all of them can be miniaturized and integrated in a microrobot by adding some extra sensors/actuators. Therefore, the concept of a capsular endoscope microrobot used to diagnose the GI tract is totally compatible with these advanced imaging techniques.

1.2.4. Microrobotics in future endoscopy

Minimally invasive procedures gives a great variety of benefits for the patient, ranging from reduction of recovery time, medical complications, infection risks, and postoperative pain to increased quality of care, including preventative care [71,72]. Since the apparition of Intuitive Surgical robot da Vinci (a minimally invasive surgical robotic system) it has been accepted that the most important skill of a surgeon is the cognitive ability, whereas technical skills required for precision and dexterity can often be delegated to appropriate technology [73]. At the small scales, there has been significant progress in robot-assisted colonoscopy [74] and in miniature robots for use in the GI tract because microrobots have the potential to perform tasks that are currently difficult or impossible, and they will undoubtedly lead to the development of therapies not yet conceived [75].

Microrobots have been envisioned for a wide variety of applications, including healthcare, micro-manufacturing, security and surveillance, hazardous environment monitoring, space exploration and others [76]. Medical application of microrobotics will be done shortly. Nowadays some microrobots have

been developed to be applied in medical or biological uses. Micromanipulation or swarm behaviour are known examples of envisioned uses of microrobitcs in medicine:

- Miniman [77] is a decimetre cubic microrobot specially designed for micro-manipulation using piezoelectric legs.
- miBot [78] is the smallest nanomanipulator microrobot.
- Micron [79] is a multi-micro robot manipulating system to handle μm-sized objects as well as smaller nano-scale objects.
- Alice, the size is 2x2x2 cm and it can run for up to 10 hours before recharging [80]. The main purpose of Alice is to design a cheap robot for the study of collective behavior in a large community of robots.
- I-SWARM microrobot, with a 1 cubic millimetre size. The robot uses three piezoelectric based actuators to move the side legs of the robot independently for controlled locomotion [81,82]. This robot has been designed to study the collective behaviour in a swarm of robots, like Alice. However, as an I-SWARM robot is smaller it is possible to add much more robots, in particular one thousand robots.

Nowadays the inclusion of some of such capabilities in medical microrobotics is still a paramount challenge due to the constraints imposed by the environment. However, as the technology permits it, the next step in the evolution of medical procedures is from minimally invasive approaches towards extremely targeted, localized and high precision endoluminal techniques performed by autonomous microrobots. These new surgical tools capable of entering the human body through natural orifices or making very small incisions and delivering drugs, performing diagnostic procedures and even excising and repairing tissue are now under development [83,84].

1.3. Capsular endoscope microrobot

In the particular case of the GI tact, examining, diagnosing and performing therapy in this region is extremely difficult due to the size of the cavity and due to difficulties to access to the entire region. Nowadays, the tools used for examining the GI tract can be divided in two groups: direct examination and indirect examination. In direct examination the tools are inserted by natural orifices like the nose, mouth or anus. These techniques are painful and cannot access the entire GI tract. Indirect examination produces less pain for the patient, however the results given by these tools are not always effective. The use of small medical microrobots to perform the diagnosis and therapy of the entire GI can proportionate the effectiveness of invasive techniques with the advantages of non-invasive techniques. Such microrobots has to necessarily be small enough in order to be introduced into the GI tract but it has to include as much functions as possible. Low power consumption is also necessary.

The advances performed in microrobotics permits to build up a small surgical capsular endoscope with the shape of a pill (approx. diameter 10 mm and length 30 mm) equipped with sensing capabilities for detecting cancer in the GI region [85] and actuating capabilities which permits to enable therapy (e.g. remove polyps, drug delivery, etc) while the capsule is diagnosing at the same time [85]. In the literature it is possible to find some examples of capsular prototypes with legs to enable active locomotion [86], liquid lens to enable magnifying endoscopy [87], a cutting mechanism or a syringe to enable therapy and drug delivery [88], etcetera.

However, nowadays in the market it is only possible to find capsular endoscopes composed by at least one camera, some LEDs, a battery and an RF transmission system. The operation of such endoscopic capsules is quite simple because the capsule is ingested orally, and from there, it starts sending images of the digestive tract. Moreover, as the digestive system is responsible of the movement of the robot, via peristalsis, the images are taken randomly. Because of its limited locomotion capabilities, capsule endoscopy is able to send images of the entire digestive system at a low frame rate. The sensing capability of the existing capsular endoscope is detecting obscure bleedings in the GI tract. Figure 1.1 shows the regions of the GI tract that can be examined with capsular endoscopes.

1.3.1. Market potential of capsular endoscopy

Diagnostic and therapeutic procedures with endoluminal access to the GI tract are one of the most dynamic growth areas in the medical markets. More than 15 million flexible endoscopic procedures are done worldwide each year [89]. The entire endoscopy market (flexible and rigid/surgical) is worth approx US$ 5 billion annually in global sales according to a survey of Millennium Research Group.

The market potential is enormous. Based on epidemiological data and current recommendations from the side of medical scientific societies approximately 30 million people worldwide should have colonoscopy screening per year. This creates a market worth EUR 6-8 billion only in examination fees at underlying current price schemes [44]. The current market for flexible endoscopes is approx. EUR 1 billion, and it is dominated today by Japanese and US companies.

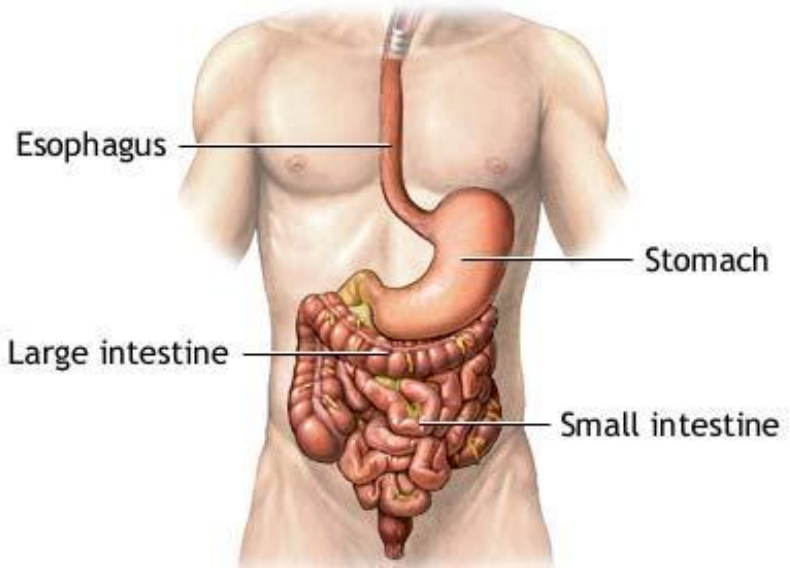

Figure 1.1: Regions that can be examined with a capsular endoscope.

While the classical endoscopes market is mature, new products, such as interventional devices and capsule endoscopes, have become the fastest growing segments in the GI endoscope market. Figure 1.2 shows the growth of capsular endoscopes in the US market.

The first wireless capsule endoscope appeared in the year 2001. It was the M2A capsule, and it was designed by Given Imaging. After that, different capsule endoscopes appeared in the market. Nowadays only 4 capsular endoscopes are available:

- PillCam SB, PillCam COLON and PillCam ESO, from Given Imaging, Israel.
- EndoCapsule from Olympus, Japan [60].
- MiroCam from IntroMedic, Korea [91].
- OMOM from Jinshan Science & Technology, China [92].

Olympus, world leader in the market for endoscopes, is the major competitor of Given Imaging. Today, Olympus has a market share above 70% in the business of endoscopy. Although it is the dominant player in the market there are other companies with other models. Even so, Olympus is the company with a higher number of patents (Figure 1.3).

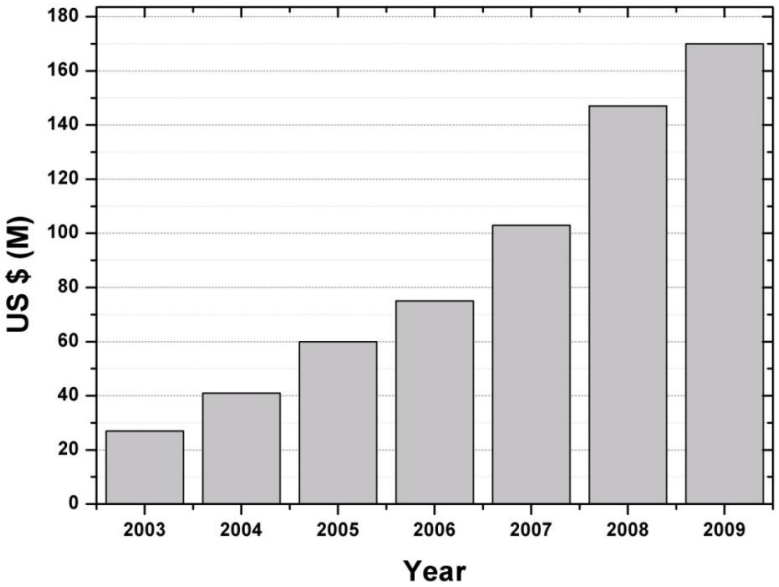

Figure 1.2: Growth of capsular endoscopes in the US market [90]

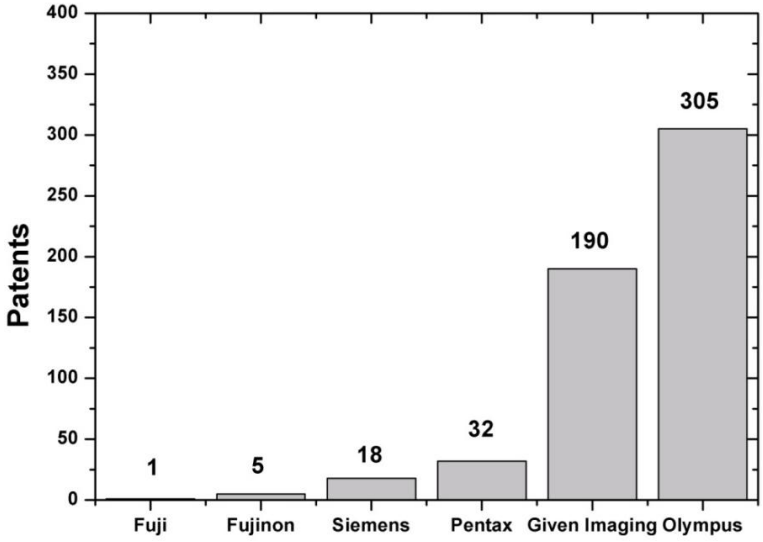

Figure 1.3: Number of patents of different companies in capsular endoscopy [93].

The global capsule endoscopy market was valued at $149.8 million in 2008. Driven by increasing awareness of the advantages of this device over traditional endoscopes and its increased utilization as the first line of diagnosis for small bowel disorders, this market is expected to grow at a CAGR of 26.3% during 2008 – 2015, to reach sales of $767.5 million in 2015 (Figure 1.4). With only 4 companies in the market at present and a high proportion of individuals suffering from gastrointestinal disorders, this under-penetrated market will provide huge growth opportunities for small and emerging companies that come up with an innovative product offering.

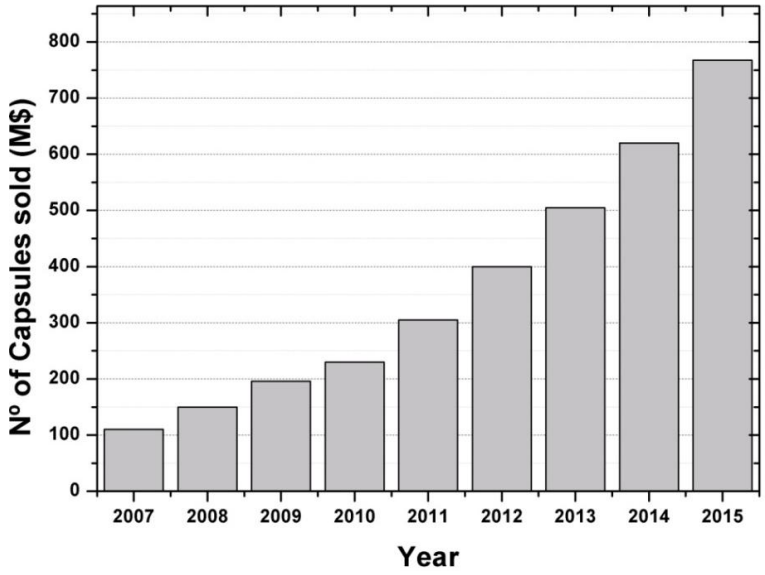

Figure 1.4: Expected market growth of capsular endoscopy [94].

1.3.2. Medical needs/trends

Endoscopy has been in use for almost three decades now. Traditionally, endoscopes used fiber optics, a powerful lens system and a light source to illuminate and visualize the interiors of body cavities and joints. The endoscopic procedure, 30 years since its inception, still remains a painful procedure to the patient. There is still a significant potential for screening colonoscopy among people, who have not made use of the opportunity to have the examination done. The Centers for Medicare and Medicaid Services estimate that only 14 % of their insured has had any kind of colorectal screening. The American Cancer Society estimates that 26 % of eligible patients have decided to undergo screening. This shows a still low market penetration in the colon cancer screening field if compared to other screening programs, such as mammography for breast cancer (70 % adoption rate) and Pap smears for cervical cancer (80 % adoption rate). A recent survey, performed by Novineon [95], identifies the fear of pain as a leading reason for patients for not having screening colonoscopy. Other reasons include missing awareness of screening endoscopy programmes and the fear of discomfort during the procedure (Figure 1.5).

These numbers show that many patients still harbour fear and reluctance to have colonoscopy done. A study presented in [96] in a group of 1284 consecutive patients demonstrated that only 27 % of colonoscopies are found painless. Therefore any new self- propelled endoscopy technique that reduces the amount of pain and discomfort for the patient will receive market appreciation, since it lowers the threshold for the individual to make use of screening offers. Thus, miniaturization of capsular endoscopes is a need.

Another major drawback that can be solved by capsular endoscopes is the visualization of the small intestine. Unfortunately flexible endoscopes or rigid endoscopes could not solve this issue in 30 years.

Despite miniaturization of capsular endoscope is the major need in this type of procedure, there are still some needs that could improve the procedure. For example, it is needed to exclude the risk of disease transmission through disposable devices. The transmission of disease through reusable flexible endoscopes is of growing concern. Cleaning and disinfection are considered effective for standard germs, if performed properly. There is growing concern with regards to the risks of prion transmission. Endoscopic supplies, such as biopsy forceps, have been banned from reuse in some countries, as a reaction on the risk of spreading Creutzfeld-Jakob disease.

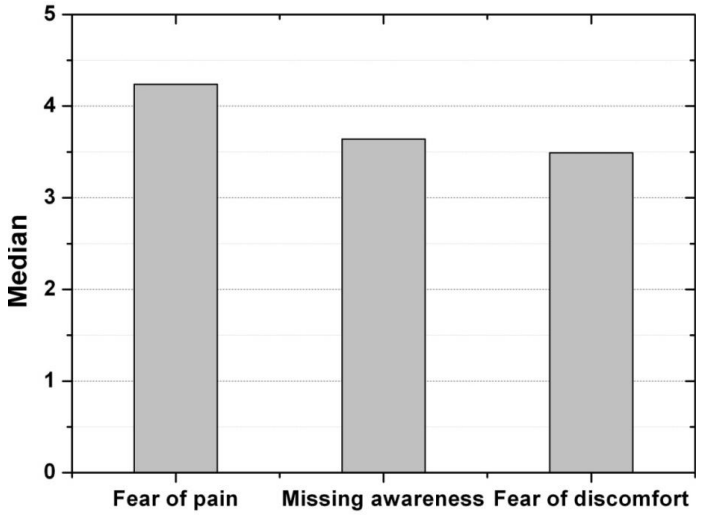

Figure 1.5: Main reason for patients for not having screening colonoscopy [95]. On a scale from 1 to 5, where 5 indicates the maximum importance. Data acquired from Novineon.

As miniaturization goes on, it is possible to add more functions to the capsular endoscopes. Integration of advanced diagnostic functions to support diagnostic precision and integration of advanced therapeutic options to make use of growing diagnostic capabilities for less invasive treatment is extremely desirable for the doctors. Figure 1.6 shows some of the new relevant features that are desirable in capsular endoscopy. High scores received the ability to rotate the capsule, the ability to stop the capsule in the GI tract, the capability to take biopsies and the ability to actively locomote inside the organ. In this regard backwards locomotion was found even more important than forward locomotion. This is maybe due to the fact that backwards locomotion is necessary to re-inspect areas of interests that have been passed by the capsule. In addition, active locomotion can solve the obstruction cases found in some patients.

Capsule endoscopy offers a simple, safe and non-invasive alternative to traditional GI imaging procedures. The procedure does not require sedation, intubation, bowel insufflation or radiation. Patients may even continue with their normal daily activities during the procedure. Despite its great advantages, capsule endoscopy is not yet the gold standard. For example, in the comparison performed in [97], the conclusion was that the use of capsule endoscopy of the colon allows visualization of the colonic mucosa in most patients, but its sensitivity for detecting colonic lesions is low as compared with the use of optical colonoscopy.

As a capsule endoscope is designed to be a portable device, the characteristics of the electronics integrated in the capsule are not the same as the integrated in a typical endoscope. For example, the quality image of a capsule endoscope is less than a typical endoscope. It raises the need of improving the

electronics for the capsule. With better electronic components, it is possible to improve the detection of diseases and it is possible to convert the painless procedure in the gold standard procedure.

New trends have been identified, that will drive the market towards painless, easy to operate, disposable and multifunctional novel smart pill type endoscope systems. Figure 1.7 shows a roadmap for capsular endoscopy. It illustrates the fast emergence of capsular endoscopy in comparison with traditional endoscopy. This fast development is strictly related to the number of functions which can be incorporated in the capsule, in addition to vision ability.

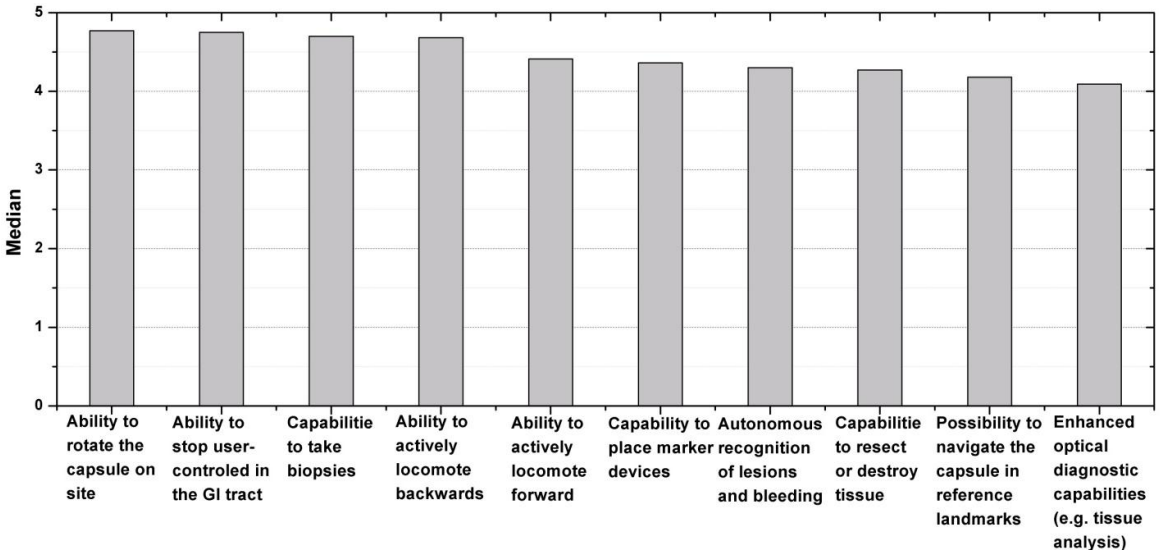

Figure 1.6: Relevant features that are desirable in capsular endoscopy [95]. On a scale from 1 to 5, where 5 indicates the maximum importance. Data acquired from Novineon.

In particular, available endoscopic capsules in the market have just the first function (imaging with passive motion) and some investigations are performed also by Olympus and NORIKA [98] to add the second feature (i.e. wireless power supply).

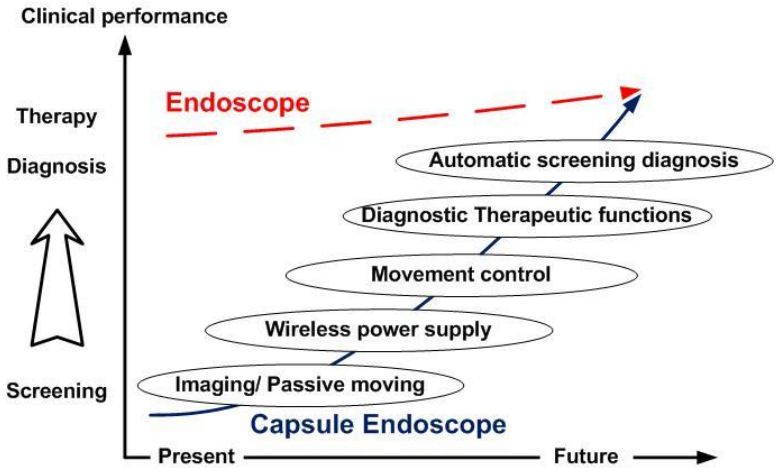

Figure 1.7: Roadmap for capsular endoscopy presented by Mr. Shimoyama, the President of Olympus, during his talk at the MicroMachine Summit 2005 (1-4 May 2005, Richardson, Texas, USA)

1.3.1. State of the art of capsular endoscopy

In the year 2001 Given Imaging presented the first wireless capsular endoscope. The capsule was equipped with simple capabilities. However nowadays there are some prototypes under study which equip the capsule with advanced capabilities and some of them also try to equip the capsule endoscope with robotic capabilities. Next, the state of the art is presented. The passive capsular endoscopes subsection presents the firsts capsular endoscopes that appeared in the market. Advanced capsular endoscopes section presents the new capsular endoscope prototypes. Finally the robotized capsular endoscope presents the new prototypes which provide the capsular endoscope with robotic capabilities.

1.3.1.1. Passive capsular endoscopes

The first wireless capsule was designed and commercialized by Given Imaging. It was the M2A capsule and it was the benchmark for the following capsules. This capsular endoscope is basically a passive capsule equipped with a CMOS camera. The capsule moves through the GI tract using the peristalsis (wave-like contractions that move food or the capsule along the digestive tract). While travelling, the capsule acquires images of the GI tract.

The M2A capsule is 26 mm long and it has a diameter of 11 mm. It is equipped with 6 white LEDs, a camera, a Radio Frequency (RF) transceiver, which permits to send acquired images in the GI tract to a data recorder worn on a belt by the patient. The M2A is capable to send 2 images per second. Figure 1.8 shows how is structured, the different parts and how is constructed.

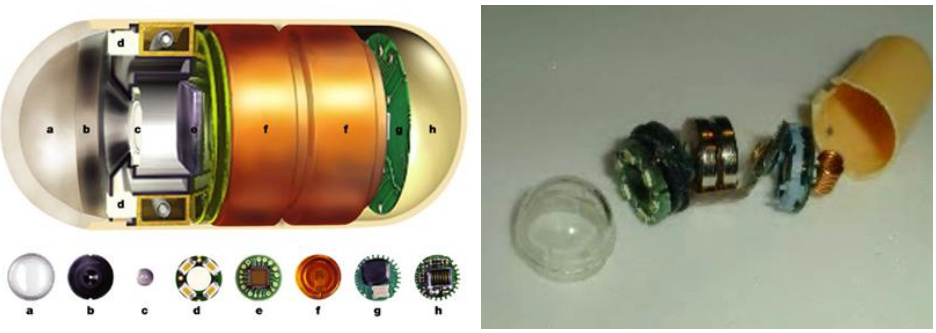

Figure 1.8: Structure of the M2A capsule endoscope ("Inside the M2A capsule" by Given Imaging).

The main parts of the M2A capsule are: a) Dome, b) Pin Hole c) Lens, d) LED, e) CMOS Sensor, f) Batteries, g) Transmitter, h) Antenna.

The second capsule endoscope that appeared in the market was the Endocapsule from Olympus (11mm x 26 mm). Figure 1.9 shows the Endocapsule, which has similar features to the M2A capsule. Basically, it has a camera sensor with more resolution, the frame rate is 2 images per second and the illumination is achieved using 6 white LEDs.

Some years later appeared the OMOM capsule endoscope [60].The OMOM pill measures 13 mm×27.9 mm, and weighs less than 6 g. The OMOM capsule has a battery life similar to the other capsules (approximately 6~8 h) and is also propelled by peristalsis. The frame rate and the operation principle is the same that the other capsules. In conclusion, the OMOM capsule is a pure copy of the M2A capsule.

These capsules, the M2A from Given Imaging, the Endocapsule from Olympus and the OMOM capsule from Jinshan Science & Technology, form the first generation of endoscopic capsules. They have

simple capabilities, only acquiring images of the GI tract and sending the images to a data recorder worn by the patient.

The next generation of endoscopic capsules basically improve the vision system. In this second generation there are new capsules which focus in different parts of the GI tract. For example, Given Imaging has designed the PillCam ESO to examine the esophagus. The PillCam ESO contains an imaging device and light source at both ends of the video capsule and take up to 18 images per second as it passes down the esophagus.

1.3.1.2. Advanced capsular endoscopes

The new generation of endoscopic capsules is equipped with more capabilities than the previous endoscopic capsules. This means the addition of more sensors and actuators, and at the end, the inclusión of more electronic devices that will help to improve the diagnosis and will enable the treatment of some diseases. Some of these new endoscopic capsules are the Sayaka capsule [98], from RF System Lab, the IntelliCap [99], from Philips and the VECTOR capsule [85].

The main characteristics of the Sayaka capsule (figure 1.10) are:

- Fluorescent LEDs, which are used to enable the fluorescent function.
- It is not equipped with battery. It is equipped with a wireless supply system.
- The camera is in one side of the capsule, and it has the possibility to rotate.
- It has two main structures. The inner part (where the camera is placed) rotates taking images of the GI tract while the external part travels through the GI tract. The rotation is achieved because the inner part is equipped with small magnets, while an electromagnet (placed in the external part) intensifies the rotation.

Figure 1.9: Image of the Endocapsule capsular endoscope from Olympus.

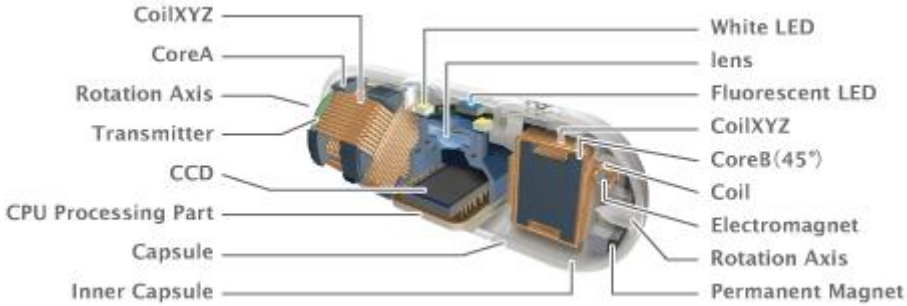

Figure 1.10: Image of the Sayaka capsular endoscope from RF labs.

In order to control the whole system, the Sayaka capsule needs a processor. The CPU processes the acquired image and the driving of the LEDs. Furthermore, the Sayaka capsule is equipped with a RF system which enables the communication with the doctors.

As the camera is rotating while traveling through the GI tract, the Sayaka capsule acquires lateral images with high definition of the GI tract. With this strategy, the Sayaka capsule is able to acquire images of the entire GI tract. It improves capsular endoscopy because the previous capsules were only able to acquire frontal images, which means that sometime the capsule could miss to acquire good images of determined regions.

The acquired images are transmitted outside the human body to the receptor. Then, the images are processed and sorted in order to show the entire GI tract, as it can be seen in figure 1.11. This big image reproduces the digestive tract, which is 6 to 8 m long. The resulting image can be zoomed 75 times.

Figure 1.11: Image processing system of the Sayaka capsular endoscope from RF labs.

The Intellicap capsule, from Philips, (figure 1.12) is not a complete endoscopic capsule because it is not equipped with a vision system, therefore it is basically a drug administrator controlled electronically. However, the Intellicap has the same size as an endoscopic capsule (11 mm x 26 mm). In addition, the Intellicap capsule is equipped with a microcontroller, a battery, pH sensor, temperature sensor, RF transceiver, a pump system to administrate the drugs and a drug reservoir.

The Intellicap capsule communicates with an external control unit using the RF transceiver.

The drug is delivered using an internal pump located inside the Intellicap capsule. This pump is controlled by the microcontroller, which allows a precise control of drug delivery. Sometimes, the medical conditions requires a progressive drug delivery, multilocated or suddenly.

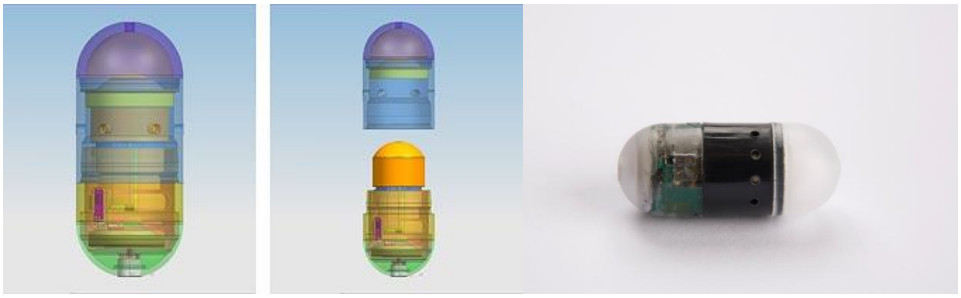

Figure 1.12: Images of the Intellicap capsule from Philips.

Preplanning the exploration permits to program the microprocessor with the correct control algorithm, which has to take into account where is located the region to be treated and how the drug will be delivered. Such program is uploaded to the Intellicap capsule before swallowing it. The sensors located inside the Intellicap capsule like the pH sensor or the temperature sensor help the microprocessor to know

the position of the capsule inside the GI tract. All data are sent via the RF transceiver to the external control unit located outside the human body.

1.3.1.3. VECTOR capsule, a robotized approach

As it happens in the previous capsules, the VECTOR capsule is equipped with vision and communications. The communication system is basically a RF link that provides information and energy to the whole system as reported in [98]. The vision system is composed by a monolithic 320×240 active-pixel RGB/gray level camera-on-a-chip sensor, designed by Neuricam [100], 16 LEDs for the illumination and an ARCTIC 416 liquid lens. The main innovation in the vision system of the VECTOR capsule is that the lens has a variable focal. It permits to equip the endoscopic capsule with a focusing system that allows obtaining better images of the selected area. In addition, the LEDs are divided in 4 groups: Red, Green, Blue and infra-red (IR). These distribution permits to acquire images using the NBI analysis and allows to do spectroscopic analysis.

In addition, the VECTOR capsule can also be equipped with a group of selectable sensors and actuators and a locomotion system. Particular sensors/actuators can be equipped for particular exploration scenarios instead of being always assembled because of area limitations. Possible sensors/actuators are pH sensing, tissue sampling, tactile sensing and drug delivery. Figure 1.13 illustrates the capsule concept. The capsule robot has some fixed elements. The control ASIC, the locomotion actuators, vision system (LEDs, liquid lens and camera), the communications interface and the powering elements are fixed.

Table 1.5 summarizes the main characteristics of the main capsular endoscopes presented in this section. The firsts two columns presents the 2 firsts capsules that appeared in the market. The other columns present the new prototypes which have advanced and/or robotic capabilities.

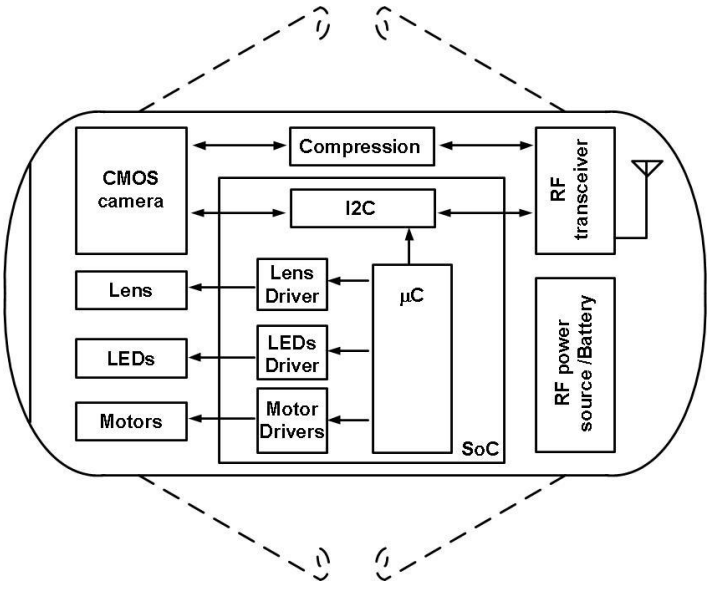

Figure 1.13: Capsule concept of the VECTOR capsule endoscope.

Table 1.5: Comparative of the main capsular endoscopes.

	M2A	Endocapsule	Sayaka	IntelliCap	VECTOR
Dimension (DxL)	11 mm x 26 mm	11 mm x 26 mm	9 mm x 22 mm	11 mm x 26 mm	10 mm x 30 mm
Operative region	Small intestine	Small intestine	Entire GI	Lower GI	Entire GI
Camera	CMOS	CCD	CCD	No	CMOS
Resolution	6 x 256 pixels	320 x 320 pixels			320x240 pixels
Frame rate	2 images/second	2 images/second	30 images/second		2-20 images/sec.
Illumination	4 to 6 white LEDs	6 white LEDs	4 LEDs	No	16 LEDs
Motion	Peristalsis	Peristalsis	Peristalsis	Peristalsis	Peristalsis/Bioinspired legs
Electronics	RF transceiver Off-the-shelf LED driver	RF transceiver Off-the-shelf LED driver	CPU processor: - Image processing - LEDs driving RF transceiver	uC RF transceiver	ASIC : - uC - Motor drivers - Lens driver - LEDs driver RF transceiver
Sensors	No	No	Fluorescent LEDs	pH (used for localitzation) Temperature	Yes
Actuators	No	No	Rotating system	Fluid pump Drug reservoir	Liquid Lens BLDC Micromotors: - Drug delivery - Tissue sampling - Legged locomotion
Other	1st commercial capsule	Real-time diagnosis	No need of battery	Electronically controlled drug delivery tool.	Active locomotion Improved vision system

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2. The VECTOR capsule concept: System architecture

Compared to traditional endoscopy, capsular endoscopy performs similar operations in a less invasive way. In order to functionally perform the same operations as a traditional endoscope, a capsule endoscope must be equipped with 3 basic functions. These functions are:

- Vision system, which illuminates the GI tract and acquires images. The vision system is composed by at least one camera and some LEDs.
- Communications system, which sends the acquired images to the receiver placed outside the human body. It can be also in charge of receiving external orders.
- Supply system, which supplies the whole capsule. The supply system can be composed by batteries or by other systems like wireless power supplier.

Although these basic functions are always needed, a capsule endoscope can be equipped with more functions (i.e. advanced functions) which will improve the diagnosis. Figure 2.1 shows a scheme with basic and advanced functions that can be added in a capsule endoscope and the components (sensors/actuators) that they need. Furthermore, figure 2.1 describes the electronics needed to enable each described function. The basic functions are those functions which are essential to build an operative capsular endoscope. The most important advanced functions that can be added are high frame rate, auto-focus/zoom, locomotion, drug delivery, biopsy and fluorescence. The high frame rate function permits to achieve more images of the GI tract and it also permits to perform the examination in real time. The autofocus/zoom functions requires the inclusion of a liquid lens (which is operated with high voltages), and it permits to acquire better images of the regions of interest. The drug delivery, biopsy and locomotion need special mechanisms in order to perform their functions, for example it is needed a microsyringe or a micropump for drug delivery, or a cutting mechanism for biopsy or some legs/vibration/magnetic system for active locomotion. Finally, the fluorescent function permits a visible detection of early stage cancer by only adding some fluorescent LEDs to the capsule endoscope [1,2].

In order to enable each function it is needed to incorporate some electronics in the capsule endoscope. Therefore, the space constraints imposed by the capsule endoscope plays an important role because they limit the electronics that can be added. In addition, the packaging of the electronics is also important. For example, enabling each function with off-the-shelf components requires much more volume than designing an ASIC with specific drivers.

The aim of this chapter is to present the architecture of an advanced capsule endoscope designed in the framework of the VECTOR project. Such capsule must include some advanced functions in order to enhance capsular diagnosis and to enable therapeutic functions. The requirements that have to be fulfilled by the VECTOR capsule are:

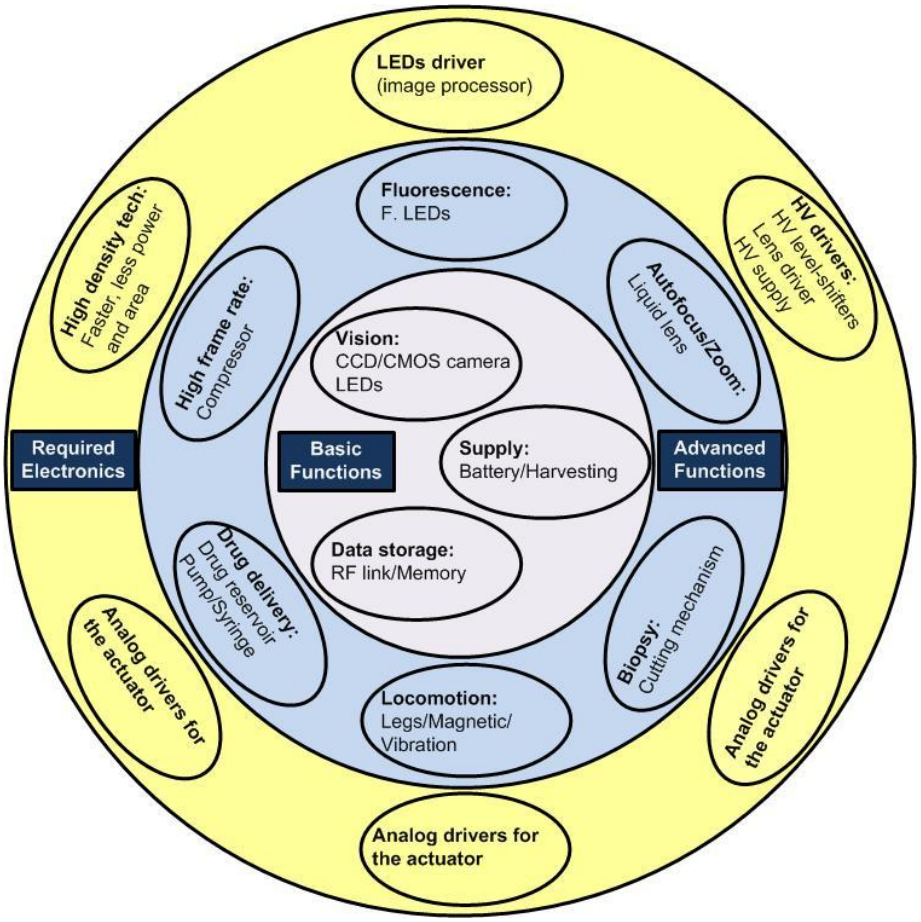

Figure 2.1: Basic scheme of the functions that can be added in a capsule endoscope. It also resumes the required electronics needed to enable such functions

- Improving image analysis. In order to improve the diagnosis the system has to be capable of performing NBI, fluorescence or spectroscopic analysis. In the VECTOR capsule these different analysis are achieved by using different LEDs in each case (e.g. for the NBI function the capsule uses coloured LEDs).

- Improving the vision system by enabling the autofocus and zoom function. This is achieved by adding a liquid lens.

- High frame-rate: the state-of-the art capsules have a low frame rate. By increasing the frame rate the doctors are able to analyse more images. Because of the limitations in in-body transceiver, to achieve a high frame-rate it is necessary to implement a compressor between the camera and the transceiver.

- Active locomotion. It permits to create space, stop and move forward and backwards the capsule inside the GI tract. The movement can be achieved by adding some legs to the VECTOR capsule or by using magnets.

- Enabling therapeutic functions like drug delivery, biopsies and/or clipping lesions.

In particular, this chapter presents two possible architectures to solve the problems related to adding these advanced functions in the VECTOR system. Both solutions takes profit of a specially designed

ASIC, which contains the electronics needed to enable each different function, because the ASIC requires less space than using off-the-shelf components.

The first proposed solution consists in a microrobot capsular device used for diagnosis and therapy. Due to the complexity of this system, the proposed solution has been to use an ASIC as a controller, which also contains the most important drivers for its application, and a Global interface for sensors and actuators (GISA) which contains the drivers needed to enable different sensors and actuators. In addition, for flexibility, the ASIC contains a microprocessor. As it is a global solution, the ASIC can work with an embedded RTO, as it is described later.

The second proposed solution consists in dividing the microrobotic capsular device in three different devices. This solution also uses an ASIC, but due to some modifications that are described next in the chapter the ASIC does not work as the controller of the system.

2.1. Towards a microrobotic solution for diagnosis and therapy in the GI exploration

As the VECTOR project pursues the goal of improving capsular endoscopy by adding advanced functions, enabling therapy and robotic behaviour, the basic and essential blocks of the smart VECTOR capsule must be: powering unit, vision system, telemetry system, locomotion system, CPU and global interface sensor/actuator platform. The powering, vision and telemetry units are the basic functions for a passive capsule endoscope. However, for an active capsule it is needed to add the locomotion function. Furthermore, as it is necessary to add more advanced functions, a global interface sensor/actuator platform has been though to add as much functions as possible. Such global interface is connected and controlled by the CPU. The CPU is required to enable the robotic behaviour of the capsular endoscope.

Due to the space limitations, the difficulties of these circuits to be added and due to the low power consumption requirements, it is preferable to use integrated circuits (ICs). For this reason, the trend for this system architecture is to unify the CPU and the locomotive system in one ASIC (the control IC). In addition, a particular solution for this system architecture is to implement the global interface sensor/actuator platform in another ASIC. Changing this ASIC changes the capsule behaviour (function). Thus the possibilities of diagnosis/therapy are unlimited as the interfaces used are standard. With this system architecture the robotic behaviour is enabled by software, in particular the system is controlled by a real time operating system (RTOS). Basically, the RTOS distributes different operations to be done in the form of tasks.

The aim of this section is to present a microrobotic capsular endoscope able to perform diagnosis and therapy in a GI exploration. First of all, a description of the components needed to enable advanced capsular endoscopy is given. Secondly, the control ASIC and the GISA ASIC are described. Finally, the software used in the control ASIC is introduced.

2.1.1. Components in advanced capsular endoscopy

Figure 2.2 illustrates the concept of the VECTOR capsule. The ASIC, the CMOS camera, the telemetry system and supply system enable the basic functions of an active capsular endoscope. In addition, as it is used for the vision system, the ASIC also includes the drivers needed for the advanced vision functions. By adding some extra electronics (e.g. global sensor and actuator interface) the VECTOR capsule can perform some advanced functions, as shown in figure 2.2. In particular, the selected actuator for locomotion in the VECTOR capsule is a brushless (BLDC) micromotor. The most important feature of this actuator is that it can also be used for drug delivery and biopsy functions.

Therefore, with the inclusion of a BLDC motor driver into the control ASIC it is possible to do 3 different functions.

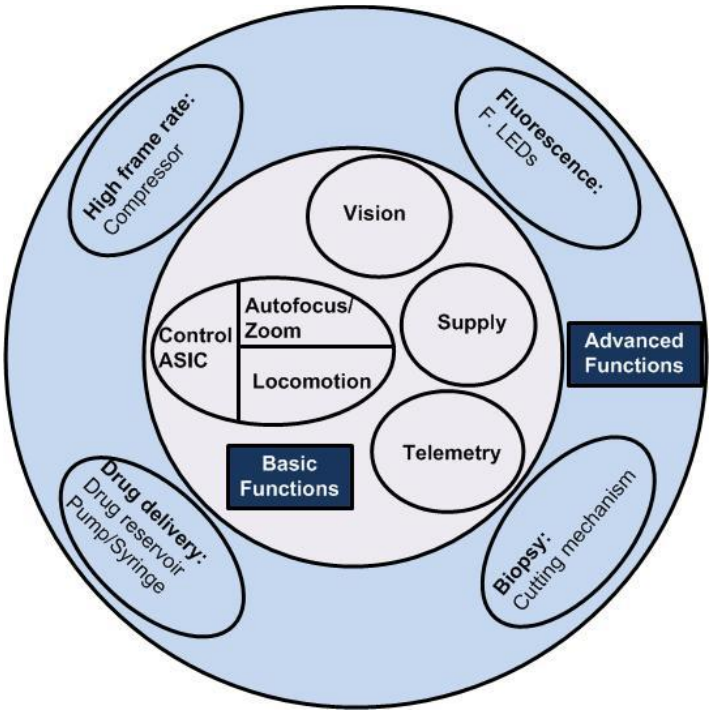

Figure 2.2: Basic scheme showing the VECTOR capsule concept.

Figure 2.3 shows a representative schematic of the System on Chip (SoC) architecture for the microrobotic VECTOR capsule. With such architecture the control IC has the control of the whole system. It controls the CMOS camera, the RF transceiver and the global interface sensor/actuator platform via the I2C bus. Taking into account the data transfers speed, an I2C bus has been selected to perform the interconnection of the different elements because it uses less wires (i.e. 2 wires), compared to other communication strategies like a SPI bus (4 wires). In addition, the I2C bus is standard and it is widely used.

The control IC is also the one in charge of blinking the LEDs, the driving of 2 different motor drivers (used to enable locomotion, drug delivery and biopsy when it is needed) and driving a liquid lens (used for the autofocus and zoom functions).

As can be seen in figure 2.3, the ASIC does not perform the compression system. Compression should be included in the CMOS camera or in the RF transceiver to reduce power. However, as it will be described later, none of them include it. For this reason, in order to enable high frame rate it is needed to add an external element which has to be able to compress the acquired images and send it to the transceiver. Furthermore, the compressor cannot be included in the global interface because of the space constrains. As it will be described later, the global sensor/actuator interface uses a long channel technology, and it basically means that the RAM memories needed by the compressor require too much area.

Finally, the system is supplied by the powering unit. Such unit is composed by a wireless power supply and a battery, which is continuously recharged by the wireless unit. However, as sometimes this

solution cannot supply the demanded energy, it is also taken into account the possibility of adding another battery instead of the wireless power unit.

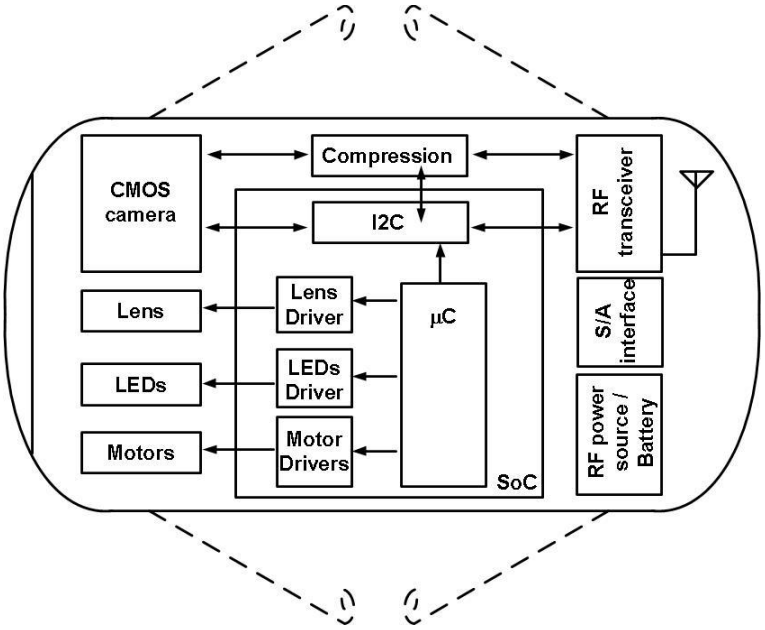

Figure 2.3: Schematic of the proposed architecture for the microrobotic VECTOR capsule.

Next, it is described in more detail each of the elements used in the proposed architecture for the microrobotic VECTOR capsule. First, it is described the powering unit, because if wires are not used to supply the capsule, it is needed to know how much power can supply the powering unit. As the primary function of a capsular endoscope is to acquire images and send them to an external receiver, the vision system and the telemetry system are described next. After that, the compression system used to reduce the amount of data of each image is described. Next, it is presented the control IC because it is used to control the whole system and to enable active endoscopy. Finally, the GISA platform is described.

2.1.1.1. Powering Unit

A bottleneck affecting all the commercial capsules is the limited available battery power, providing typically 25mW for 6-8 hours [3]. This amount of power is barely sufficient for low resolution images transmitted at low data-rates and certainly not enough for actuators and highly consuming modules. In the VECTOR capsule, a 3D inductive link is used to supply up to 400 mW [4]. A schematic of the wireless power module is depicted in figure 2.4. Details of the 3D inductive link can be found in [4,5].

In order to take full advantage from wireless power transfer, an energy storage system is also implemented to provide high current peaks when needed. This would also allow to store energy during low power states, when the capsule needs just a fraction of the amount of power transmitted through the inductive link. The energy storage unit is obtained by a supercapacitor connected to the wireless power transfer and to the modules that would require high current peaks.

2.1.1.2. Vision system

The vision system, one of the basic functions for any capsule endoscope, is formed by a CMOS camera and 16 LEDs. The CMOS camera acquires images while the LEDs illuminate the GI tract. In particular, the camera is a monolithic 320×240 active-pixel RGB/gray level camera-on-a-chip sensor that

has been developed by Neuricam [6]. It is drivable by an I2C input and output is available in parallel or through an LVDS serial output. It has been fabricated using 0.18µm CMOS technology from UMC.

For the illumination, the solution is to use narrow bandwidth color LEDs switched on alternatively at high frequency to deliver a composite white light illumination. This solution has the great advantage to allow recording white images and chromatic images with a single illumination unit.

The illumination ring is composed of 4 color groups. Each color group uses 4 identical LEDs. All LEDs used in the illumination unit were selected from Kingbright taking into account their peak wavelength, emission angle and optical power. These 4 groups of LEDs could be easily replaced by 4 conventional white LEDs. Figure 2.5 shows the vision system formed by the CMOS sensor and 16 LEDs.

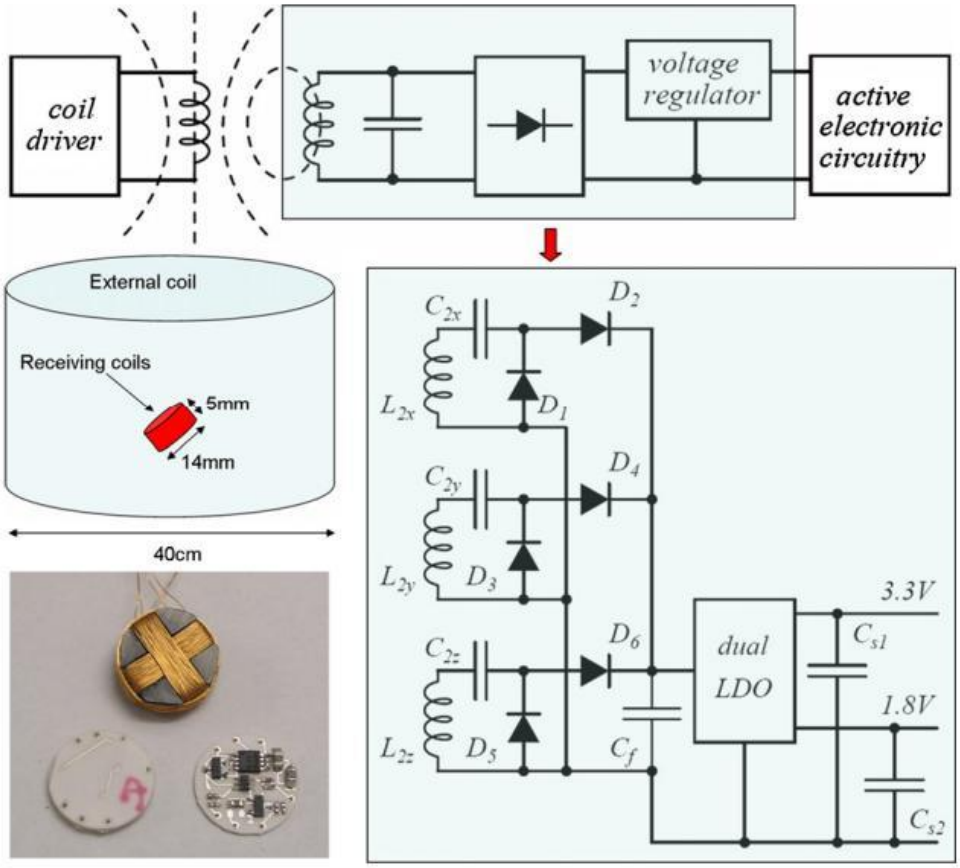

Figure 2.4: General principle underlying inductive powering systems (top) and schematic of the multiple receiving coil-set (right). At the left, spatial arrangement of the coil composing the power module (top) and a detail of the 14 mm ferrite-coil receiver before assembling (bottom) [4]. With permission of Riccardo Carta.

2.1.1.3. Telemetry system

The endoscopic capsule needs a bidirectional data transmission for its correct operation, the endoscopic capsule has to receive orders from the medical doctors and it also has to be capable of sending the acquired data outside the human body. The downlink from the capsule to the outside world must be able to transmit a large amount of data. In addition, the available data rate defines the image quality of the endoscope. However, to get a high data rate one needs to increase the radio frequency of the carrier wave of the signal; but the higher the frequency, the higher the absorption of the waves by the human body. As the available power for the transmission is limited, a dedicated 2 Mbps FSK near-field transmitter has

been designed and implemented to the endoscopic capsule. Further details of the transmitter are given in [7]. Figure 2.6 shows the transmitter.

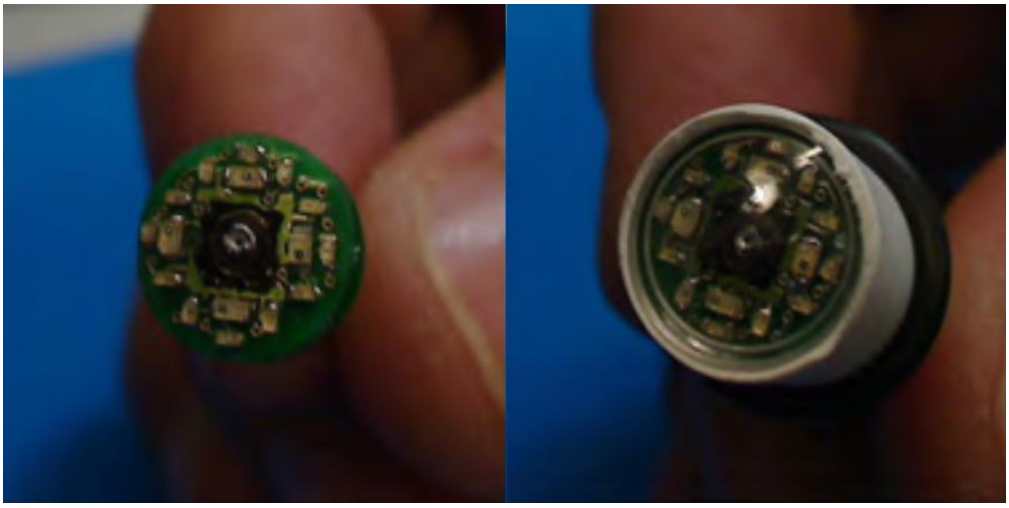

Figure 2.5: Vision system of the VECTOR capsule.

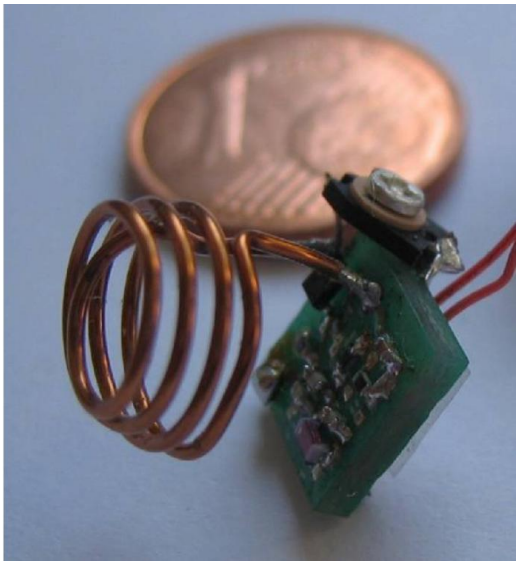

Figure 2.6: Assembled FSK transmitter with coil antenna. Image taken from [7]. With the permission of Jef Thoné.

2.1.1.4. Compressor

The compressor is used to reduce the amount of data of each acquired image. This is done to reduce the data to be sent and to reduce the time needed to send each image. With this strategy it is possible to increase the frame rate of the capsular endoscope. Nevertheless, in the VECTOR system the camera sends the images with a fixed frame rate. As the included transceiver cannot send at the fixed frame rate it is necessary to add a compressor to reduce the amount of data.

There are several compressors in the market, like the JPEG compressor. Due to power limitation, small size conditions and specific image data format, traditional image compression techniques are not

appropriate for this application. The solution is to use dedicated compression techniques. The proposed algorithm is based on integer version of discrete cosine transform (DCT) and wavelet transform (DWT) and Huffman entropy coder. Thanks to integer DCT/DWT application it has low complexity and power consumption [8]. The compressor can be integrated in the CMOS camera, the RF transceiver, the control ASIC, in a devoted ASIC or it can be programmed in a FPGA.

2.1.1.5. Control IC

Looking at the basic features implemented on the commercial capsule endoscope, 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. The selected strategy in the VECTOR capsule microrobot has been to integrate the control system plus the drivers needed to enable illumination, active locomotion and auto-focus in a specially designed ASIC. With this solution the space and the power consumption needed by the electronics are reduced compared to other solutions like using off-the-shelf components.

Beyond the trivial problems of integrating additional electronics on the same space, the difficulties arise to manage, consuming the minimum possible power, the actuators which enable the robotic functions. As the design and description of the ASIC are the particular aim of this thesis, we can find a more detailed explanation of the control IC in section 2.1.2.

2.1.1.6. GISA platform

Although the proposed system containing a powering unit, the vision and telemetry units and a control IC enables active capsular endoscopy and advanced vision functions, it is still a limited solution. In some cases it would be useful to have more information about the GI tract, like knowing the pH or the Temperature. Is in these cases where the concept of the GISA takes sense.

Designing a GISA ASIC capable of driving a selection of different sensors and actuators the system can be completed to perform so many different functions. As it is a complement, the GISA has to be controlled by the control IC via I2C. More detailed description of the GISA platform can be found in section 2.1.3.

2.1.2. Detailed description of the control IC

One of the key issues in the design of an ASIC is to correctly select the technology taking into account the application of the circuit, the available power consumption and the available area. For this reason, in this section the technology selection is detailed first. Next, it is described the design process strategy and the design tools used during the design of this ASIC. Finally, the architecture of the ASIC, the design of the drivers and the implementation results are described.

2.1.2.1. Technology selection

The definition of the technology for the fabrication of the ASIC is a very important part in the design flow. Considering that only some technologies are available in Europe at low cost, that not all the features of the technology are available for prototyping users, and the requirements to integrate the advanced functions, the technology selection has to be done at the beginning of the design flow.

To fabricate the ASIC several technologies have been evaluated. It has been taken into account the integration density, the power consumption and the powering and driving voltages required for the capsule elements. All the technologies evaluated are available through Europractice Consortium or through Circuit Multi Projects (CMP) which offer low cost fabrication through Multi-Project-Wafer (MPW). On Table 2.1 there is a summary of technologies which can be used to design the IC for the

VECTOR project. Deep-submicron technologies cannot be used in VECTOR because of the high-voltage requirements.

Table 2.1: High Voltage Technologies Available in Europractice and CMP

Technology	L (um)	Price (€)	V (core)	V (I/O)	Runs/Year
AMIS I2T100	0.7	600/mm2	5	5 / 100	5-EU
AMIS I3T80	0.35	990/mm2	3.3	3.3 / 80	4-EU
AMS CXZ	0.8	650/mm2	3.3 / 5	2.5 / 50	3-EU
AMS H35b4	0.35	1000/mm2	3.3 / 5	20 / 50	4-EU/4-CMP

The maximum voltage required for the liquid lens of the capsule is 60V, although the driving can be done at 50V. The high voltage technologies presented on table 2.1 are designed to achieve voltages from 50V to 100V. Comparing these four technologies a higher integration is obtained with a lower characteristic size, which is obtained with AMIS I3T80 and AMS H35b4. Between these two possibilities it has been chosen Austria-Micro-System (AMS) H35b4 technology which can work with four metals, in front of the three metals on AMIS technology, giving the possibility to reduce the interconnections complexity and also the total area required for the system. Further reasons to choose the AMS technology is that EEPROMs can be available in the H35b4 technology. EEPROMS are not available for low-volume users in any other technology offered by Europractice or the CMP (even in deep-submicron technologies). Additional reason is the experience of the group working with AMS for more than 10 years.

So, the silicon provider chosen to fabricate the control ASIC is AustriaMicroSystems to which we will access through Europractice. The technology used has to deal with the high voltage capabilities and medium density of integration. The technology has a characteristic feature size of 0.35um, 50V voltage capabilities and 4 metal layers. The voltage required to power the systems is 3.3V. An additional 50V voltage is required to control the liquid lens proposed for the vision system. It is a mixed-signal technology which is usually used on automotive industry, which ensures a long time life. The most important features of the technology are summarized on Figure 2.7.

2.1.2.2. Design process and tools

The design of an ASIC from the scratch is risky because it is easy to make a mistake or because some circuit could not work as expected. As the VECTOR ASIC uses different analog drivers, which have not been used by our group before, it is preferable to fabricate and test these circuits before sending the final ASIC. For this reason, the design process to fabricate the control ASIC for the VECTOR capsule consisted in:

- Design and fabrication of two mini ASICs containing analog drivers.
- Test of the mini ASICs using an external FPGA to control them.
- Modification of the drivers (if needed).
- Design and fabrication of the control ASIC prototype containing the analog drivers and their controllers.

During the design of these ASIC prototypes we also have used analog IPs bought by the foundry, in this case AMS.

We have used different software tools depending on the design stage. The design process of our group uses the golden tools recommended by Europractice, The analog design is done using the IC software from Cadence. For the synthesis of a digital design it is used the Design Compiler software from Synopsys. It has been also used the CoreConsultant software from Synopsys to integrate the 8051 processor. For the place and route it is used the Encounter software from Cadence. Finally, for the verification of the system it is used the Calibre software from Mentor Graphics.

AMS HIGH VOLTAGE TECHNOLOGY OVERVIEW (MPW):

Process technology specifications	units	H35B3D2	H35B4D3	CXZ
Drawn LVMOS Channel Length	µm	0.35	0.35	0.8
Operating voltage LV-MOS **	V	3.3 , 5	3.3 , 5	5
Number of masks	#	24	27	17
Number of Metal Layers	#	3	4	2
Number of Poly Layers	#	2	2	2
Max. operating voltage HV-NMOS	V	50	50	50
Max. operating voltage HV-PMOS	V	50	50	50
specific R_on* HV-NMOS	Ohm mm^2	0.11	0.11	0.34
specific R_on* HV-PMOS	Ohm mm^2	0.29	0.29	0.8
Max. gate voltage	V	3.3 , 5 , 20	3.3 , 5 , 20	5 , 20
Propcess features				
high resistive poly		v	v	v
substrate related LV devices		v	v	v
thick metal layer			v	
5V gate oxide		v	v	
20V gate oxide		v	v	

Figure 2.7: AMS Technologies Features

2.1.2.3. Control ASIC architecture

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 choice in the VECTOR capsule depends mainly 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 2.8 shows the architecture of the SoC. The main block of the SoC is the embedded 8051 microprocessor which is the control unit (DW8051 IP provided by Synopsys© [9]). The inclusion of the microprocessor into the endoscopic capsule gives more flexibility to the system and facilitates the debug. In addition, as the functions of the capsular endoscope are not known in detail, the addition of a purely hardware finite state machine (FSM) is excluded. The microprocessor also permits to add robotic functions to the capsule endoscope by enabling them by software. The large experience of our design group on the DW8051 processor has discarded the use of other microprocessors, although it would be possible to use them. Finally, the 8051 processor is a very common processor in the industry and has many different tools for software development.

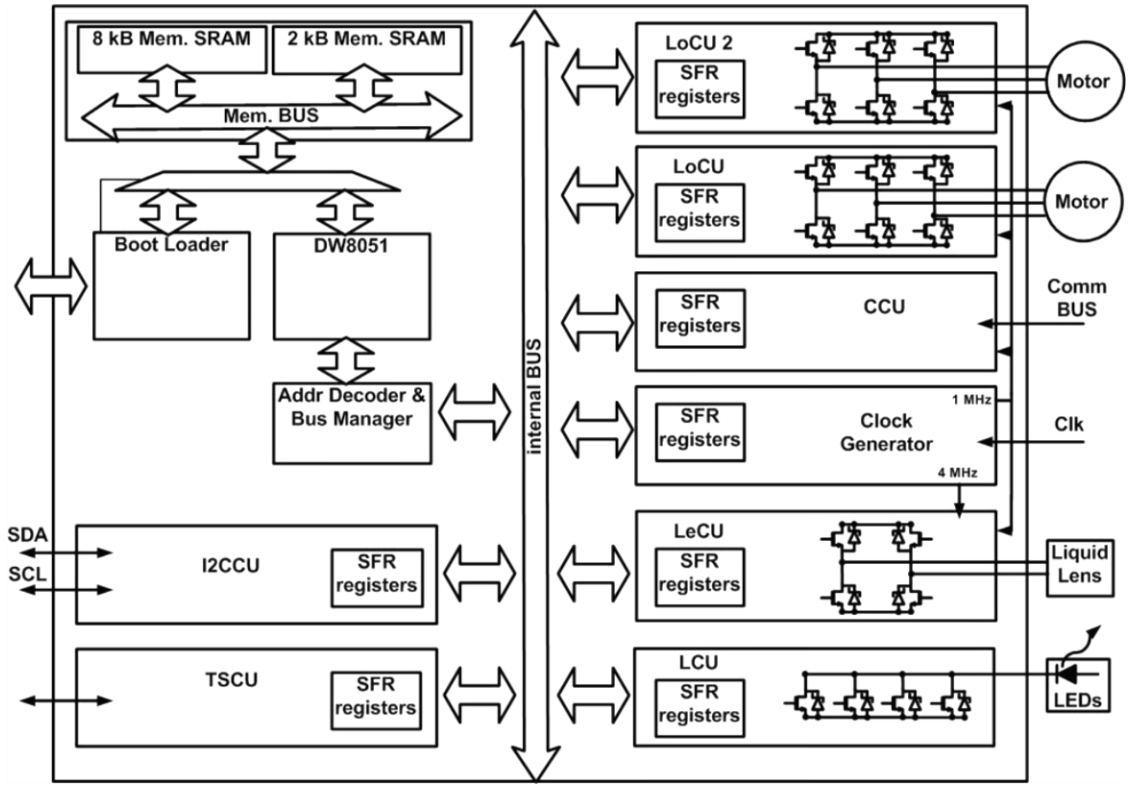

Figure 2.8: Architecture of the SoC.

The microprocessor has 256 B of SRAM internal memory, which is the minimum required. It also has 2 kB SRAM of data memory and 8 kB SRAM of program memory. This numbers have been selected from the experience in previous developments [10]. After the test of the ASIC it will be possible to exactly determine the amount of memory that is really needed. The memory type used is volatile. Therefore, each time the VECTOR capsule is powered 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 the serial port to a particular program memory area. After the program is uploaded a Power On Reset is done to the processor and configuration registers.

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, in contrast to program in the processor these functions, allows to administrate the instantaneous power to do not overpass the powering capabilities.

The time stamp control unit (TSCU) is a FSM that sends information to the transceiver indicating when an event has occurred. Basically it sends timing information to know when the image has been taken.

The I2C control unit (I2CCU) is also a FSM programmed to work as a Master I2C. As I/O pads with pull up resistors of 1 kOhm are not available in the 0.35 um HV technology from AMS, two external resistors have to be used with open drain outputs to assure the correct operation of the I2C bus.

The clock generator unit (CGU) is a simple digital block used to distribute the clock inside the chip. When the external clock enters to the ASIC it is immediately managed by the CGU. The CGU is also used to generate the clock signals for the communication module, the LoCU, LeCU and LCU modules.

The communications control unit (CCU) is a FSM which receives data from the telemetry system. It has to decode the received data and send it to the microprocessor. The data is received at 4'8 kHz by a serial input. Therefore, the RX channel is used to send orders and information to the control ASIC. The communication link permits to control the capsule endoscope from outside.

The RX channel is usually in the sleep mode. To start the receiving process, the transmitter must send a logic one followed by the data (16 bits). Once received, the CCU generates an interruption (INT0) and it returns to the sleep mode. The interruption is processed by the microprocessor.

The LEDs control unit (LCU) is composed by a basic FSM which controls the current and the period to blink the LEDs and the LED driver. The LED driver is composed of 8 transistors in parallel, with the Drain pins connected to the LED. Each transistor has a different W/L ratio to control the amount of current that each transistor drives. With this strategy, it is possible to control the current that passes through the LED controlling thus the intensity of LEDs. Figure 2.9 shows the schematic of the LED driver. There are 4 LED drivers in the ASIC, one LED driver for each 4 LEDs.

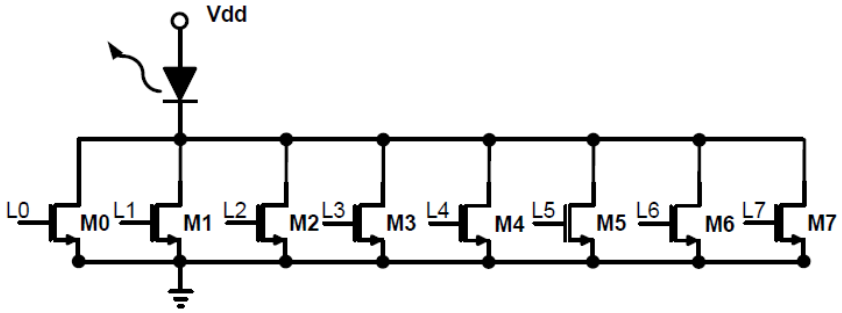

Figure 2.9:. Schematic of the LEDs driver.

Finally, the lens control unit (LeCU) and two locomotion control units (LoCU) are used to enable advanced vision functions and locomotion respectively. Both control units contain a FSM used to generate the controlling signals and the analog electronics needed to drive the respective actuators. More detailed information is given in chapters 3 (Towards legged locomotion and therapy in a capsular endoscope robot) and 4 (Enabling advanced vision functions in active capsular endoscopy).

The presented architecture has been though to use an embedded real time operating system (RTOs) in order to enable the robotic behavior by software. Although there are several operating systems (most of them real time) the ASIC is designed to use the tiny RTO from keil. A more detailed description of the RTOs is given in section 2.1.4.

2.1.2.4. Implementation results

The die photo is shown in figure 2.10. The size of the SoC is 5.1 mm x 5.2 mm. The SoC needs 2 external capacitors of 36 nF and 300 nF, and an external inductor of 220 uH. Table 2.2 resumes the main characteristics of the ASIC.

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. Further details of the test are given in [11,12].

A graphical user interface (GUI) application written in JAVA language has been developed to communicate with the PIC18F2500 through USB port. Figure 2.11 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.

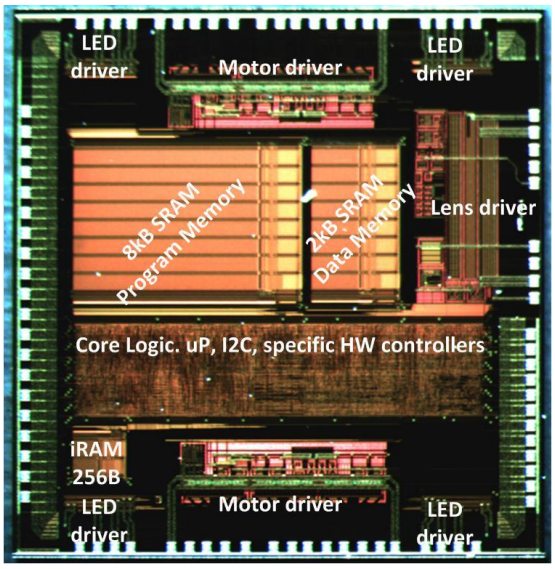

Figure 2.10: Die photography.

The wired capsule prototype allows us to measure the power consumption. Figure 2.12 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 LoCU 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 regime. 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).

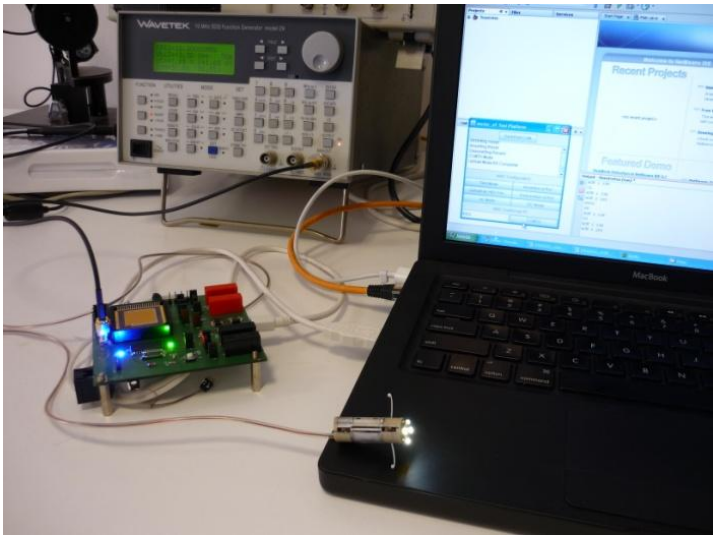

Figure 2.11: Image of the Test board and the Capsule prototype.

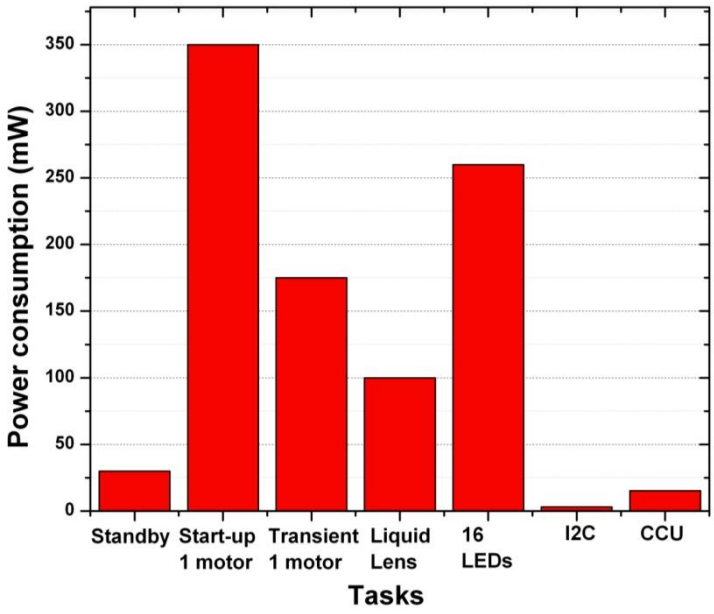

Figure 2.12: Measured power consumption.

2.1.1. Global interface sensor/actuator platform

The main function of the GISA platform is to complement the VECTOR capsule by adding more functions than the included by the principal system (power, vision, telemetry and control units). Such functions are enabled by adding more sensors and actuators to the capsular endoscope and controlling their operation with the GISA platform. As there exist so many sensors and actuators in the market that could be used to enable different functions, the GISA platform has to be prepared to deal with different ranges of voltages, frequencies, etcetera. In order to give more detailed information about the GISA platform this section is divided in two parts: sensors interface and actuators interface.

2.1.1.1. Sensors Interface

The sensors interface must be able to work with the proposed sensors of the capsule. Table 2.3 summarizes the sensors which can be found on the different endoscope systems available and envisaged in the VECTOR capsule. Classical endoscope systems use a vision system based on a CCD camera and an optical fibre to illuminate the working area. The endoscopic capsules developed by Wang [13] and Given Imaging [14] contain a vision system composed of a camera and LEDs to illuminate the area. The VECTOR capsule has a CMOS camera with an illuminating system, and a set of passive and active sensors. Passive sensors do not require actuation from the capsule, while active sensors require driving signals and control. The sensors different of the vision sensor are connected to the interface ASIC.

The aim of the GISA is to provide a platform to connect several sensors/actuators with different capabilities and for this reason the sensor interface has to deal with a wide range of input signals. To deal with this issue a programmable interface is proposed. The basic elements of the interface must provide the capability to measure currents and voltage signals from pA to uA and from uV to mV. This is obtained with a first stage, composed of an I2V converter, an analog filter and a programmable gain amplifier. The features of this first stage can be selected to provide different services to the user. These analog signals must be converted into digital values by using an A/D converter. Finally the digital value is transmitted to the CPU by the I2C bus.

A large amount of biosensors can be found on the literature. A general overview of piezoelectric biosensors can be found on [15]. On table 2.4 it is summarized the most important features of some existing biosensors.

Table 2.2: Characteristics of the presented ASIC.

Characteristic	Property	External devices needed
Size	5.1 mm x 5.2 mm	
Thickness	700 um	
Num. of pins	84	
Functions	Time Stamp	
	LED drivers	16 LEDs
	Liquid lens driver	220 uH
		300 nF
		Liquid lens
	BLDC driver	36 nF
		BLDC motor
	Master I2C	2 pull up resistors (1 kOhm)
	Communication unit	

Table 2.3: Endoscope sensors

Endoscope element	Sensors
Classic endoscope	Camera
Capsule endoscope	Camera
VECTOR capsule	Camera Temperature PH Pressure Spectroscopic diagnostics Ultrasound based diagnostics Biosensors

2.1.1.2. Actuators Interface

Classical endoscope systems have a large amount of actuators which are used to remove biologic material to make an external biopsy or to eliminate tumorous biomaterial (TMT medical). Another kind of actuation elements used in classical endoscopes are elements to create space inside the bowel, such as balloon dilators. The commercial Given Imaging Capsule does not contain any kind of actuation mechanism [14]. The Wang endoscopic capsule [13] contains a micro-current stimulus driver to stimulate

the muscle of the digestive tract to shrink and push the capsule forward. The VECTOR capsule contains a locomotion/space creation system which allows the capsule to move forward and backward and even stop the movement in the bowel. Tissue sampling and clipping actuators can also be incorporated. Table 2.5 summarizes the actuators which can be found on the different endoscope systems available and envisaged in the VECTOR capsule.

Some of the possible actuators of the capsule are grippers, syringes or scalpels. On table 2.6 some micro-grippers and their actuation signals are summarized. The actuators found in the literature require the use of a driving with high voltages and current. The limitations established by the technology chosen for the fabrication of the control electronics have to be considered in order to decide which type of actuator can be used in the capsule. For maximum simplicity, driving with square waveforms (on-off, PWM) at the full digital range of voltage (0-3.3V) is better.

Table 2.4: Biosensors on the Literature

Sensor	**Input signal**	**Driving signal**	**Interface**	**Reference**
Guided Cell Growth biosensor	-700 uV – 100uV	Pulses to contract muscle	Amplification and filtering, ADC	[16]
Bioterrorism Agents	Resistance drop -10 kΩ – 1.1 MΩ	--	Multimeter	[17]
Electrode Supported biosensor	0 – 20 nA	-100 – 300 mV	--	[18]
Solid-state Urea Biosensor	0 – 180 mV		Diferencial input	[19]
DNA-Polypyrrole Biosensor	0 - 300 uA	0 – 0.7 V	--	[20]
Amperometric biosensor	2.25 – 2.65 V (alter I2V)	-650 – -800 mV	I2V converter, amplifier, DAC	[21]
Interdigitated u-electrodes biosensor	0.05 – 0.5 pF	AC signal response 100kHz – 0.1Hz	Electrochemical Impedance Spectroscopy	[22]
Glucose biosensor	0.4 – 1.6 uA	3 electrodes method	Diferencial input	[23]
Phenylalanine biosensor	5 – 35 mV	3 electrodes method	Impedance transform, amplification, ADC	[24]
Cell-Based Biosensor, Fluidic system	10.5 – 22.5 uV	--	--	[25]
Biosensor array	10 pA – 10 uA	AC signal 0.1Hz – 10 Hz	Electrochemical Impedance spectroscopy	[26]
Electrochemical Biosensor Arrays	10 pA – 10 uA	Sinusoidal: 1Hz – 1kHz 50mV AC 1.65 V DC	Potentiometric or amperometric readout	[27]

Table 2.5: Endoscope actuators

Endoscope element	Actuators
Classic endoscope	Long oval cups with/without spike Serrated cups Aligator grasper Along rat tooth stent remover Rat tooth graspers Tripod graspers Fork 1x2 graspers Achalasia balloon dilators Billiary dilators Biopsy forceps Cytology brushe Filtration / Injection kit Helical Retrieval baskets Polipectomy shares
Given Imaging Capsule	No actuators
Capsule endoscope	Micro-current Stimulus Driver
VECTOR capsule	Locomotion/space creation Stopping Tissue sampling and treatment

Table 2.6: Micro-Actuators on the Literature

Actuator	Driving signal	Feedback	Reference
Micro-gripper for an Ultrasonic Manipulator	AC signal 20V	Piezoresistor force sensors	[28]
Parallel-plate electrostatic micro-gripper	50 – 100V	Voltage measurement	[29]
Piezoelectric micro-gripper	0 – 72 V	Micro-force sensor	[30]
Piezoactuator	AC signal 3kHz, 0 – 60 V	Piezoelectric sensor	[31]
Shape Memory Alloy Gripper	0 – 700 mA	--	[32]

2.1.2. Integration Hardware/Software

The presented control ASIC is based on an 8051 microprocessor. It is then needed to program the microprocessor with software. As the system operates in real time it has been used a real-time operating system (RTOS). An RTOS is an operating system (OS) that has been developed for real-time applications. This type of OS is not necessarily efficient in the sense of having a high processing capacity. The specialized programming algorithm, and sometimes a high rate of interruptions of the clock can interfere with processing capacity. The main characteristics of a RTOS are:

- It does not use memory.
- Different tasks can be executed when receiving different events.
- Multi-architecture (the code can be used in any processor).

- Predictable time response for electronic events.

Although modern microprocessors are usually faster for general purpose activities, when programming a RTOS it is preferable to use a processor as predictable as possible, without pagination. All factors that add randomness makes it difficult to prove that the system is feasible.

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.

Typically, each task can be under execution, ready or blocked. Most of the tasks are blocked most of the time, and only one task is under execution by the microprocessor. In simple systems, the list of tasks prepared for the microprocessor is short, basically 2 or 3 tasks.

The ASIC has been programmed with the RTX51 tiny RTOS from keil. Taking into account the previous points, different tasks has been created for the control ASIC. In figure 2.13 is shown how the tasks are structured.

- The task in red is only executed one time, just during the start-up.
- The yellow task is the main task. It is in charge of calling/executing the rest of tasks depending on the orders received by the communications port. It is always waiting for the interrupt coming from the CCU.
- The blue tasks are the ones in charge of modifying the configuration of each block depending on the received external orders. They are not active until they get the external order.
- The Interrupt Service Routine (ISR), the orange task, contains the code that will be executed when an interruption is received in the microprocessor (in particular, the interruption received in timer 1).

Finally, an example of how the RTOS works in the presented system can be found in figure 2.14. In the example it can be seen how the tasks are structured and activated.

2.1.3. Conclusions of the proposed microrobotic solution

The next step needed to make capsular endoscopy the golden standard procedure in endoscopy consist in improving the diagnosis functions and enabling therapeutic functions. The solution proposed in this subsection consists in equipping a capsule endoscope with robotic functions. Such robotic functions can be enabled by equipping the capsule endoscope with more sensors and actuators, needed to increase the capabilities, and adding a control system, which will control such sensors and actuators. Instead of using multiple chips, the solution has been to concentrate all the control electronics in a unique chip which is able to generate high current and voltages required for today actuators in microrobotics.

In addition, the ASIC can be programmed with an RTOS which permits to control the capsule robot in real time. This allows the capsule robot to act according to the input stimuli and devote more efforts to events which are more important.

The microrobotic solution with the implementation of a RTOS improves 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. However, the microrobotic solution has still some problems due to space limitations and power consumption requirements.

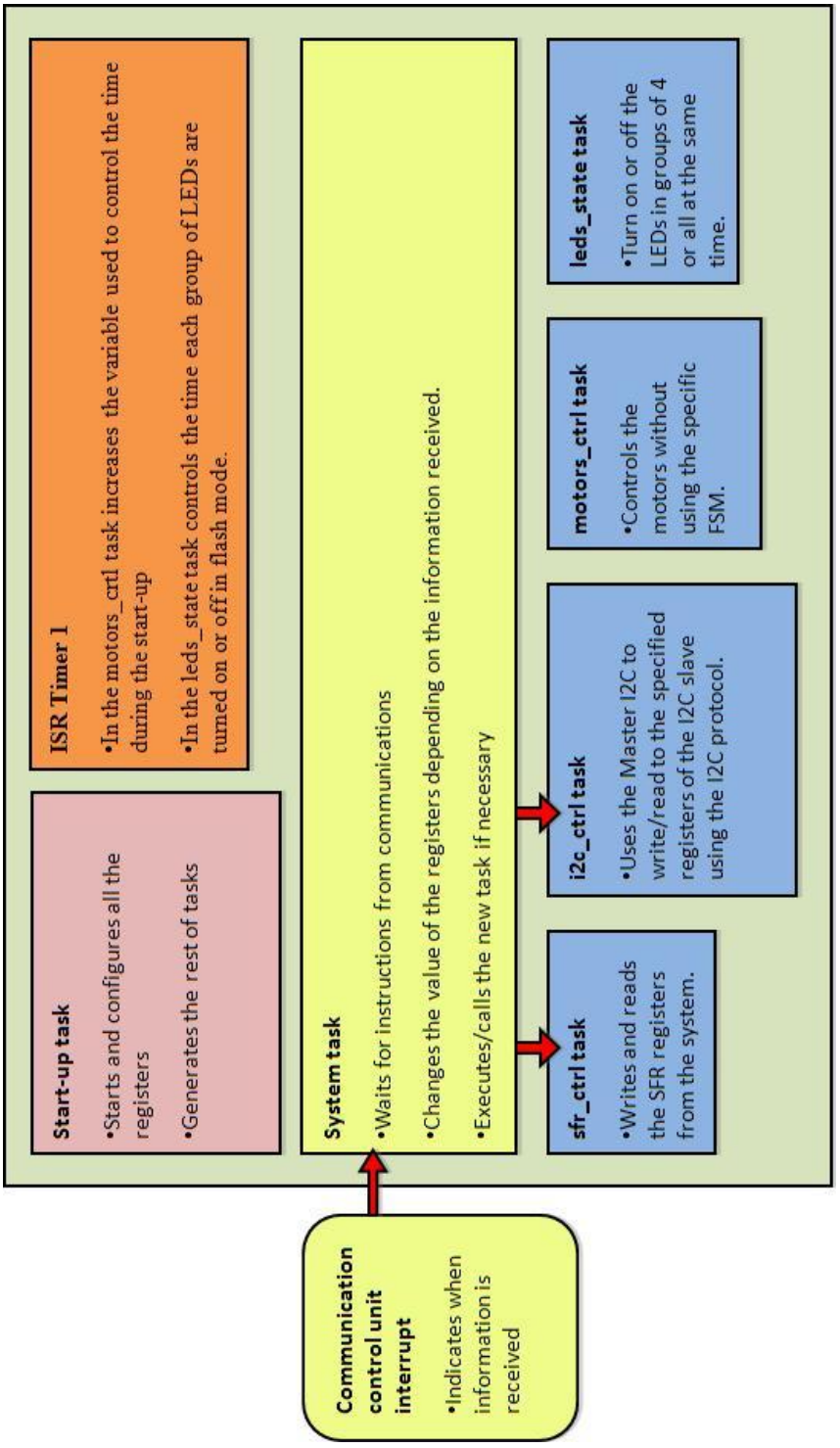

Figure 2.13: Block diagram showing the structure of the RTO tasks.

Although miniaturization of sensors, actuators, control electronics, telemetry system, wireless power system, compression system, CMOS camera and illumination system is a fact when it is done separately, the inclusion of all these elements in an small capsule of reduced dimension is still a challenge. In particular, for the presented microrobotic solution, the diameter of the capsule microrobot is 10mm and the length is 33 mm, which is bigger than the state of the art capsule endoscopes. Furthermore, the addition of so many elements to the capsule robot increases the power demand. Despite the fact that the wireless power system is capable of supplying 400 mW, it is not enough power for the capsule robot to perform more than one task simultaneously.

Besides, the addition of the compression to the presented capsular endoscope introduces a problem because it cannot be integrated in the control IC due to the technology selection. It was finally implemented in a small FPGA (silicon blue FPGA). However the best solution is to integrate it in an IC specially devoted for this operation. The use of a FPGA in the system makes unnecessary a control ASIC with all the functions described. Only the driving circuits for the motors are relevant.

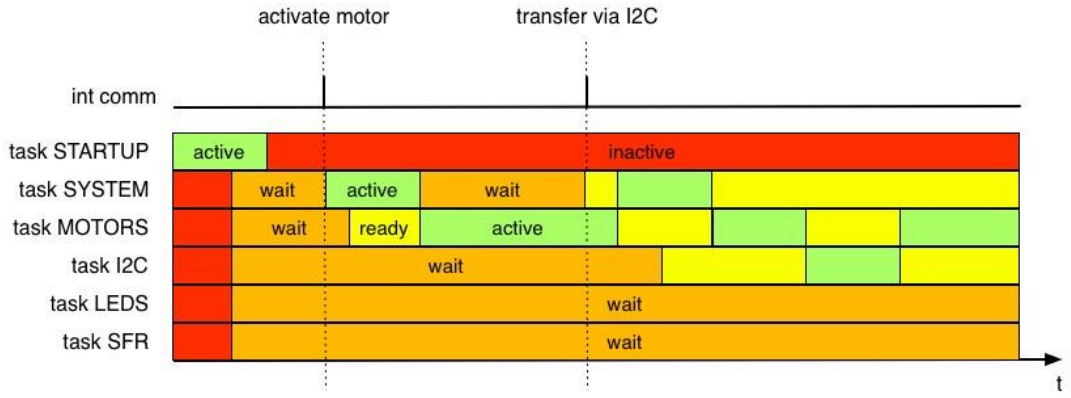

Figure 2.14: Example of how the tasks are structured and activated.

2.2. A more feasible approach for a microrobotic capsule

The all-in-one microrobotic solution has demonstrated to be not feasible at the moment. The capsule robot is equipped with too many functions. It enlarges the size of the capsule because each new function needs the addition of more sensors and actuators inside the capsule. In addition, sometimes the capsule robot can only perform one function because the power consumption is too high. Thus, it has no sense to equip the capsule robot with some functions when only one can be active.

To achieve a real capsular endoscope capable of improving the diagnosis and enabling therapeutic functions the solution is to divide the all-in-one microrobotic device into three different capsules with different functions and specifications: screening capsule, diagnostic capsule and therapeutic capsule. The screening capsule is an improved passive capsular endoscope which acquires images of the GI tract. The diagnostic capsule is an active capsular endoscope used to diagnose diseases. Finally, the therapeutic capsule is used to perform therapy.

The three wireless endoscopes can include the ASIC as the controller of the system. Nevertheless, as it is needed to add a compressor because neither the camera nor the transceiver includes it, two solutions are proposed. Figure 2.15 presents the architecture of the proposed solutions.

The first one consists in a redesign of the control ASIC to include the compressor. The main problem for this solution is that the technology chosen is not the appropriate for this application (long channel, high voltage). The second one consists in using a small Field Programmable Gate Array (FPGA) designed in a short channel (65 nm) technology. Such FPGA can perform the compressor function in the diagnostic capsule and the FPGA can also be reconfigured to perform other functions in the other capsules. As the FPGA fulfills the requirements it has become the main controller of the system, relegating the control ASIC to a slave position.

In this new architecture scheme it is needed to slightly modify the IC to enable the slave operation, improving the power consumption of the ASIC and reducing the area occupied. The three wireless endoscopes are specialized for application in one of the three essential steps in the management of GI cancer (screening, diagnosing and therapy) therefore the architecture of each wireless capsule is different from one to another and the inclusion of the ASIC only takes sense in the therapeutic capsule.

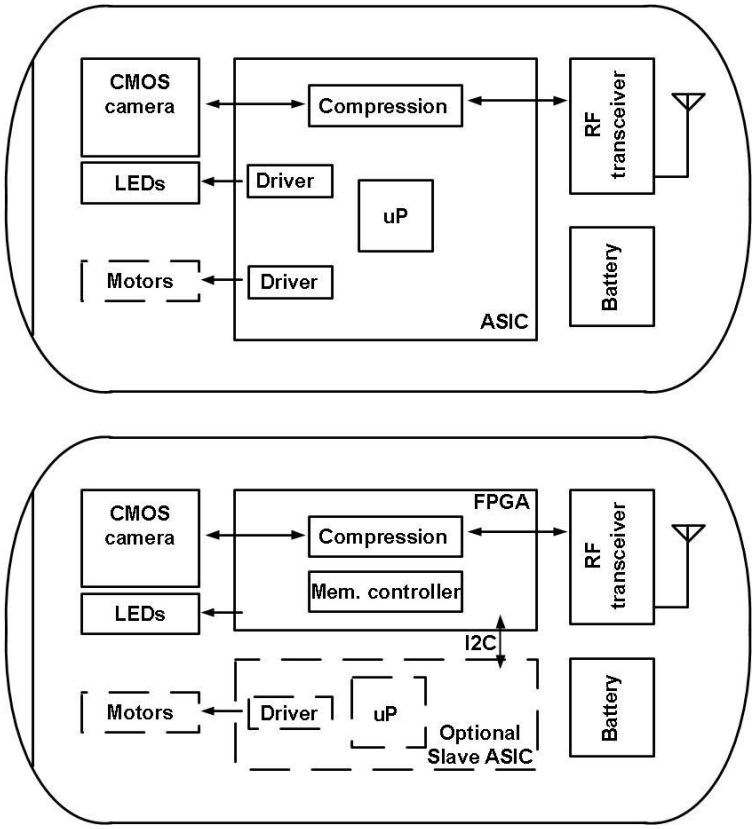

Figure 2.15: Architecture of the two proposed solutions. The first one includes an ASIC with compression included. The second one uses a FPGA as a controller and optionally an slave ASIC.

2.2.1. Screening capsule

The architecture and application of the screening wireless endoscope is price-driven in order to address a mass market. Screening incorporates both image acquisition and data storage in a wireless endoscope for the first time. Figure 2.16 shows the architecture of the screening capsule. In the screening capsule the control is performed by the FPGA, which controls the CMOS camera and blink the LEDs. Alternatively it would be possible to use the ASIC acting as a slave to drive the LEDs, however it has no sense because the FPGA can drive the entire system.

The FPGA is also programmed to send the acquired images to the flash memory. Basically, the FPGA stores the acquired images from the CMOS sensor at a low rate (2 fps) in an internal buffer and then writes the data into the flash memory. The screening capsule is supplied by batteries.

With the screening capsule the endoscopic procedure is simplified. Basically, after appropriate bowel preparation, the patient takes the screening pill on its own responsibility. When the examination is done the patient has to retrieve the screening capsule from the toilet and send it to the doctors. As the images are stored into the flash memory, the doctors have to download them into a pc before performing the examination. During the examination the patient does not require to wear any extra-corporeal device. In addition, equipment is not necessary to be purchased by the examiner. The wireless endoscope itself is the only device required for examination.

The screening capsule addresses the mass market of population by being optimized for low-cost, de-centralized application.

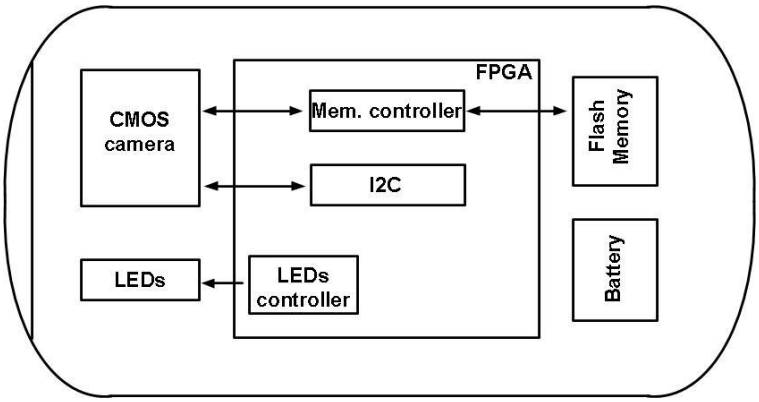

Figure 2.16: Architecture of the screening capsule.

2.2.2. Diagnostic capsule

The features of the diagnostic wireless capsule are made for high performance organ inspection and tissue evaluation. The diagnostic capsule offers active locomotion, real-time video stream, a spectroscopic sensor system for optical biopsy and sensors for capsule localization.

The architecture of the diagnostic capsule is presented in Figure 2.17. In the diagnostic capsule the control is also performed by the FPGA, which controls the CMOS camera, the RF transceiver and blinks the LEDs. In addition, the FPGA is programmed to compress the acquired images from the CMOS sensor and send it to an external receiver via a RF link. An inertial sensor is placed and controlled by the FPGA to know the position of the capsule during active locomotion. The diagnostic capsule is also supplied by batteries.

The active locomotion system has been changed in this new solution due to the power demand of the BLDC motors and because of the fragility of the legs. In particular, the active locomotion is done by adding a magnet inside the capsule and using a robotic-arm, with another magnet to move the capsule through the GI tract. Figure 2.18 shows a picture showing the magnetic arm with the magnet. The endoscopist can control the position and orientation of the capsule while observing the video image in real-time. This speeds up examination time and allows manoeuvres which are not possible with state-of-the-art endoscopes. The position of the diagnostic capsule is continuously tracked in absolute coordinates.

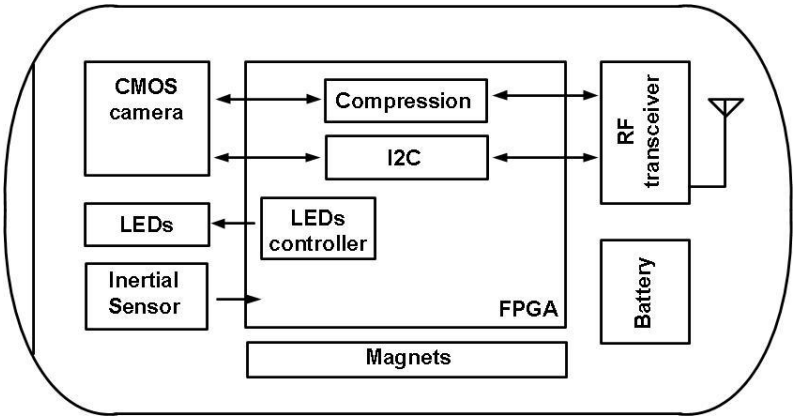

Figure 2.17: Architecture of the diagnostic capsule

For this procedure, the patient has to swallow the diagnostic capsule. The patient has to remain in the hospital during the examination because the doctors have to guide the capsule.

2.2.3. Therapeutic capsule

The therapeutic capsule is not exactly a capsule endoscope. In particular it is a part of a capsule endoscope. The therapeutic capsule is an additional shape which is equipped to the diagnostic capsule. This shape contains the surgical tools needed to remove polyps, clipping lesions or drug delivery and the slave ASIC used to enable the surgical tools. In the case of clipping lesions, the surgical tools consist in a clip, which clips the lesion, a BLDC motor which releases the clip and the slave ASIC used to drive the BLDC motor. Depending on the form of the clip, it is also possible to use it to perform biopsies. Figure 2.19 shows a CAD of the therapeutic capsule equipped with the clip.

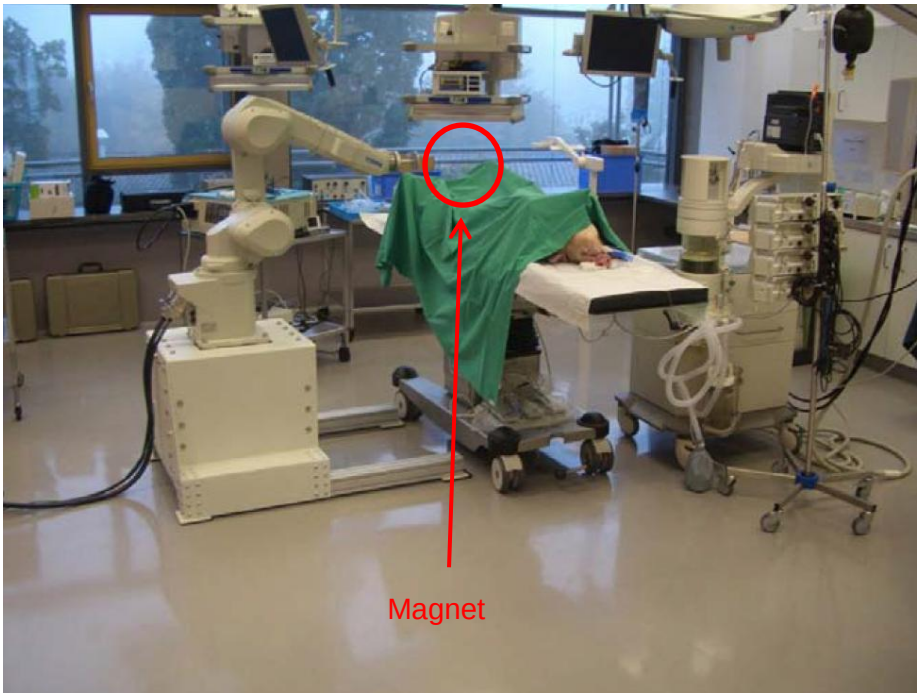

Figure 2.18: Robotic arm including the magnet.

Figure 2.19: CAD of the therapeutic capsule equipped with the clip.

As the core of therapeutic capsule is the diagnostic capsule it is needed the same equipment as for diagnosis. The procedure for the therapeutic capsule is a bit different. It is introduced into the colon through the anus. The endoscopist is able to actively guide the capsule to an identified lesion. Then the endoscopist can remotely enable the capsule to remove a polyp, to perform drug delivery or to clip a lesion.

2.2.4. New architecture of the ASIC

Accordingly with the 3 capsule concept, the ASIC has been slightly modified in order to enable slave operation reducing power consumption and reducing its size. Modules which are not needed in the current scheme of the endoscope and that have high power consumption have been eliminated. This is, for example, the case of the liquid lens driver.

Figure 2.20 shows the architecture of the new SoC. The main block of the SoC is still the embedded 8051 microprocessor which is the control unit (DW8051 IP). The microprocessor has 256 B of SRAM internal memory. After the test of the previous ASIC, it was determined that the maximum amount of memory needed to embed a RTO was 512 B SRAM of data memory and 4 kB SRAM of program memory. Hence, the new ASIC has 512 B of data memory and 4 kB of program memory. The memory type used is still volatile. In addition, the new SoC includes a Power Management Unit (PMU) which controls the clock and power signals of each block. An example of the PMU use, when the Power-on-Reset wakes up the ASIC, the PMU only activates the BL which will read an SPI EEPROM and program the internal memory. This process is carried out at 10 kHz in order to reduce the power consumption. Once programmed, if the ASIC is in master mode it wakes up the uP. When acts as a slave, the ASIC waits orders that will be send via the I2C bus. The rest of the blocks will be down until the PMU receives the order to wake them. With this strategy the power consumption is reduced considerably at the start-up.

The new ASIC also includes two motor drivers, a CCU, 4 LEDs drivers (each one can drive 4 LEDs) and an I2CCU which can also work as slave. The slave mode permits the user to use/configure the SoC externally. The external control can directly drive the motors and the LEDs in this mode.

After the test of the first ASIC we know that the LEDs need less current than prevented and we have reduced the LEDs driver accordingly to the new specifications. Therefore in the new ASIC half of the circuits are needed to drive the same number of LEDs.

The die photo is shown in figure 2.21. With the reduction of memory and the elimination of some blocks the area has been highly reduced; the size of the SoC is 3.65 mm x 3.85 mm. The SoC needs 2 externals capacitors of 36 nF for its correct operation. To achieve enough volume reduction inside the capsule the ASIC is also thinner. This new ASIC has 300 um width instead of 750 um of the previous prototype. Table 2.7 presents the main characteristics of the new ASIC.

The procedure for testing was simple (figure 2.22). A microcontroller (PIC18F2550) is used to configure the ASIC each time we want to perform a new operation. The ASIC is connected to the sensors/actuators. The microcontroller is also used to communicate with the ASIC via the communication module. It can also be configured as an I2C slave. The measured power consumption is shown in figure 2.23. Compared to the previous prototype, it can be seen that the reduction of the power consumption achieves the 95 % in some cases.

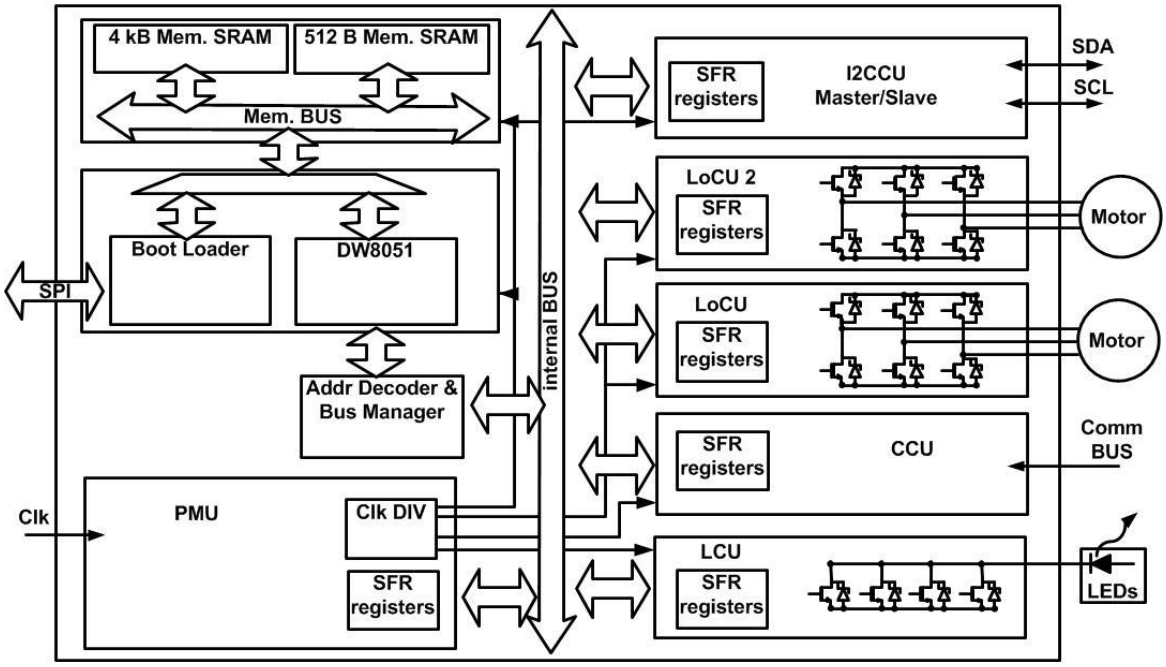

Figure 2.20: Architecture of the SoC.

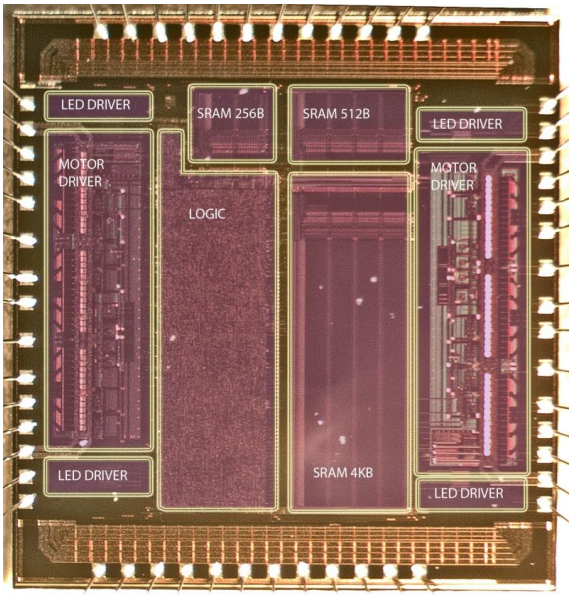

Figure 2.21: Die photography.

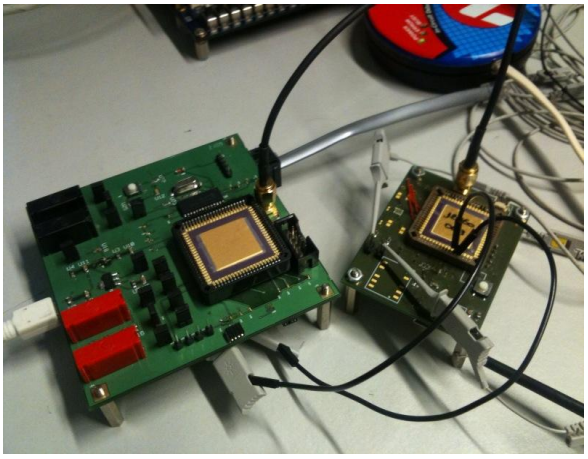

Figure 2.22: Image of the Test platform.

Table 2.7: Characteristics of the presented ASIC.

Characteristic	Property	External devices needed
Size	3.65 mm x 3.85 mm	
Thickness	250 um	
Num. of pins	67	
Nº equivalent gates	20 k	
Memories	1 SRAM (4 kB) 1 SRAM (512 B) 1 SRAM (256 B)	
Analog circuits	2 DAC (8-bits) 6 Comparators 2 3-phase inverters 2 Charge pump 1 Power on Reset 6 Level-shifter	
Modules	LED drivers	16 LEDs
	BLDC driver	36 nF
		BLDC motor
	Master/Slave I2C	2 pull up resistors (1 kOhm)
	Communication unit	

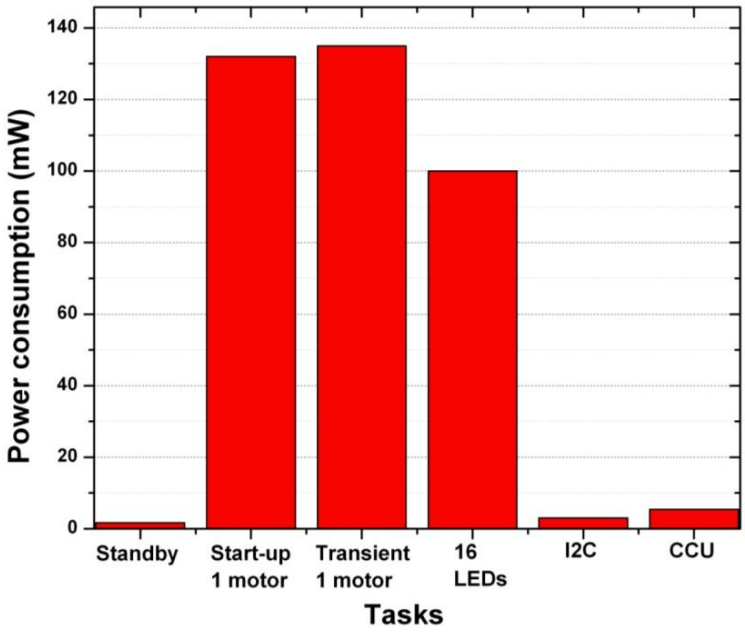

Figure 2.23: Measured power consumption.

2.3. Conclusions

In this chapter two different solutions of a capsular endoscopes has been proposed and presented with the aim of improving capsular endoscopy. The first solution proposes an active capsular endoscope which is equipped with vision, locomotion, communications and a supply system. It can also perform advanced functions like drug delivery, therapy, fluorescence and it can also acquire images at a high frame rate.

As this first solution has demonstrated to be unfeasible, a second solution proposing to split up the all-in-one device into three different capsules has been presented. Compared with the all-in-one device, the main drawback of this architecture is that it needs at least two explorations to detect and treat a polyp: one exploration with the screening/diagnostic capsule to find the polyp and one exploration with the therapeutic capsule to remove it.

The all-in-one device solution proposes an ASIC as the master controller of the capsular endoscopes. The three devices solution can also use an ASIC as a master controller, however it has more sense to use the proposed FPGA as a master of the system and the ASIC as a slave in the therapeutic capsule.

The first ASIC presented in this chapter is designed for the all-in-one device is 5.1 mm x 5.2 mm and it includes 2 motor drivers, a liquid lens driver, 16 LEDs driver, I2C master controller, communications controller and a microprocessor. The second design was done for the three capsular devices. It has been slightly modified to add new capabilities while reducing power consumption and area. The new ASIC is 3.85 mm x 3.65 mm. As can be seen in figure 2.24, the reduction of area is about 47 %.

The main improvements, comparing the new ASIC with the previous prototype, are that the final ASIC is able to auto-program itself from an external SPI EEPROM memory and it is equipped with a power management unit that permits to reduce the power consumption to less than 1.5 mW when there is no activity. The IC has two operation modes: In the first one it is used as the Master of the system, controlling all the elements of the capsule; in the second one the ASIC is used as Slave. Basically the uP is switched off and another master can switch on/off the motors and the LEDs via the I2C bus. The main changes of this new architecture compared to the previous architecture are the memory reduction, the

elimination of the liquid lens and some LEDs drivers, the addition of the PMU and the way to program the ASIC.

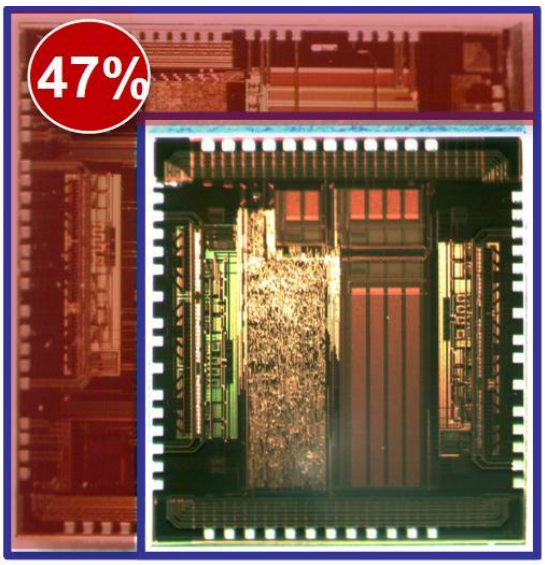

Figure 2.24: Picture of the 2 designed ASICs comparing their sizes. The big ASIC is the first prototype, while the small one is the final prototype. It is achieved an area reduction of 47 %.

With this new architecture the power consumption has been highly reduced. It can be seen in figure 2.25 a comparison of the power consumption of the main task between the two ASICs. The power consumption reduction is highly reduced in some tasks. For example, in standby the new ASIC consumes 36 times less power than in the previous prototype.

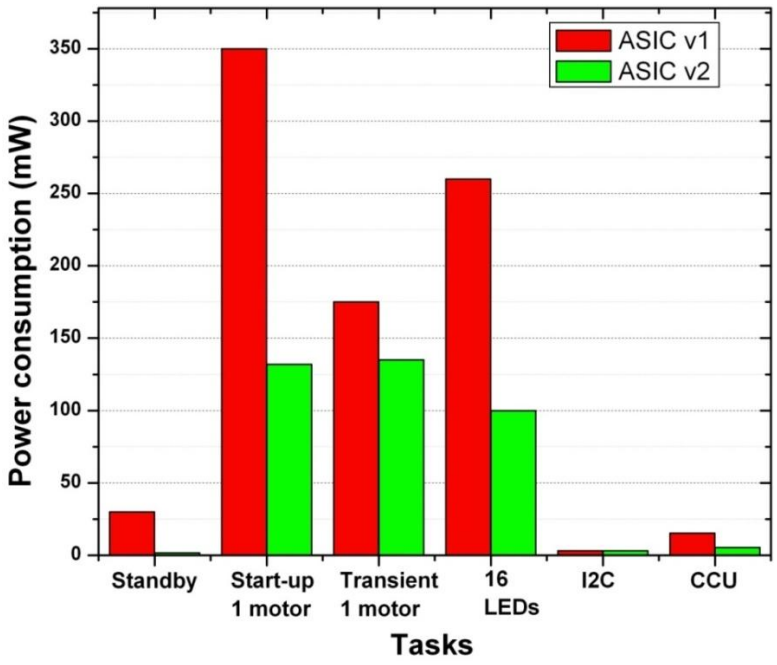

Figure 2.25: Comparison, between the two presented ASICs, of the power demanded by each task.

In capsule endoscopes it is unusual to have a control chip because capsules are usually passive, sending sensor data through a communication link. With advanced functions in capsule endoscopes this approach is not enough. The Vector capsule is a wireless endoscope with advanced vision features and therapeutic capabilities. We present in this work the first control chip, an ASIC, which can manage both diagnosis and therapeutic functions of the vector endoscope with optimal performances compared with off the shelf solutions in terms of area and power.

In conclusion, although the system architecture of the capsular endoscope has been changing during the European project, it has been presented an ASIC with reduced dimensions and low power consumption which is capable of controlling a capsule endoscope and it is also capable of enabling locomotion and therapy. In addition, thanks to the flexibility of the ASIC, which can also be used as a slave, it has been finally implemented in a therapeutic capsule endoscope.

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3. Towards legged locomotion and therapy in a capsular endoscope robot

Currently there exist different versions of capsular endoscopes like PillCam [1], OMOM [2] or Endocapsule [3]. Their main advantages like reducing the discomfort and pain or accessing to previously inaccessible regions of the GI tract are well reported [4-6]. Although capsular endoscopes have existed since the year 2001 and are currently being used successfully to diagnose the small bowel, 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.

This lack of active locomotion makes this type of capsular endoscopes to be useful only in narrow regions of the GI tract, like the small bowel. Wider regions, like the stomach or the colon, cannot be completely explored as it is not possible to move the capsule to acquire images of the whole region. Active locomotion is expected to permit to explore in detail the entire GI tract. Furthermore, it enables other fields like therapy, because with active locomotion it is possible to stop the capsule endoscope in a certain region and perform therapy. After 11 years since the appearance of the first capsular endoscope, it is clear that enabling active locomotion is challenging. However, it is also clear that it is only possible to enable active locomotion in two different ways: internal and external locomotion.

The aim of this chapter is to present the part of the ASIC presented in chapter 2 that integrates the control and the drivers needed to enable active locomotion in a capsular endoscope robot. The election of the correct locomotive strategy is presented in section Analysis of locomotive strategies for capsular endoscopes. In such section an internal locomotive solution is selected. In particular, active locomotion enabled by DC/BLDC motors is selected. The description of the electronics needed to drive such motors and the design of such circuits are described in section Electronics for DC/BLDC motors. After that the results of the designed drivers are given in section Results. Finally the conclusions are presented.

3.1. Locomotive strategies for capsular endoscopes

The challenge of cancer prevention asks for reliable devices focused on GI exploration and intervention. Several research groups focused their attention on developing application based micro-robot which locomotion able to deal with tubular, slippery and tortuous surface like esophagus, stomach or bowel.

There are mainly two possible approaches in the selection of a locomotion system for endoscopic capsules:

- An external approach which implies the development of a locomotion system completely outside the capsule, to be worn by the patient or to be put around him/her.

- An internal approach which implies, on the contrary, the development of a miniaturized and flexible locomotion system integrated on-board the capsule.

The goal of developing an external locomotion system for capsular endoscopy has been approached via magnetic fields:

- Olympus Corporation has proposed an endoscopic pill able to rotate and translate backward and forward if stimulated by external magnetic fields (Olympus Guidance System).

- It is also possible to include a permanent magnet within the capsule [7] in order to increase the forces applied to the capsule by the external field.

- Carpi and co-workers [8] proposed a solution exploiting a magnetic shell to be applied to traditional capsules prior to their use. The shells are capable of interacting with an imposed external magnetic field, thus providing a means to control the capsule movement and orientation. This solution is readily and cheaply applicable to any commercial endoscopic capsule, thus avoiding internal modifications.

The main advantage of an external locomotive approach is that it is less restrictive in terms of power than an internal approach because the capsule endoscope is not spending power from the batteries to move along the GI tract. On the opposite side, the main disadvantage is that neither the Olympus system nor the other presented systems are capable to exactly position the capsule inside the GI. Therefore this locomotive system works by trial and error, making this solution not intuitive for the medical doctors. Another disadvantage is that this external locomotive strategy needs bulky external driving systems for the generation of dynamic magnetic fields [9]. Such driving systems are expensive and, hence, the price of capsular endoscopy is increased.

Several locomotion strategies have been proposed by research groups which selected the internal approach. Different internal locomotive strategies have been reported, some of them are presented next:

- Park et al. [10] proposed a new paddling based locomotive mechanism for endoscopic capsules. The presented locomotive mechanism is originated from the task of paddling a canoe. The paddles of a canoe are embodied as six legs equal spaced on the circular surface of the device and the canoeist is replaced by a linear actuator (a commercial stepper micromotor). The actuation mechanism is composed by a lead screw and two mobile cylinders. The outer diameter of the capsule is about 13mm and the total length is 30mm. This robotic capsule is able to travel the small intestine with an average speed of 2.7mm/s.

- Jung Jae Hun et al. [11] proposed to examine the intragastric conditions of a patient by using a microrobot swimming in his/her stomach previously filled with water. The microrobot should comprise a main body unit, a tail unit (its rotation results in the movement of the main body in the liquid), and a driving unit having an end arranged in the main body unit so that the driving unit is rotatable. The driving unit should be connected to the tail unit and should generate driving forces to rotating the tail unit. The main body unit is thought to be equipped with a camera for obtaining image information.

- An interesting driving mechanism for endoscopic capsules was presented by Ikeuchi et al. in [12]. The developed actuation system is based on a rotating rib which generates motion through its contact with intestinal mucus. Since driving force is caused by hydrodynamic effect, direct contact of

the rib with the tissue is not necessary for traction. The measured thrust force generated by this device was up to 1N when gap width was small and sliding speed was high.

- A vibration motion mechanism was presented in [13]. It is a motion principle based on the interaction of centripetal forces, which are generated by a rotating mass mounted on a robotic device, with the frictional forces arising from the interaction of the device with the locomotion environment, as well as with gravity. Potential benefits for the proposed locomotion method include: a self-contained locomotion method, integrated inside the capsule, without any external protrusions (legs, paddles, etc.) and potential for bidirectional movement capability (forward and reverse motion).

- Karagozler et al. [14] presented a stopping and locomotion mechanism, based on six legs with 2 degrees of freedom, useful for an endoscopic microcapsule robot. The mechanism is connected with a compression spring and a hollow cylinder forming a piston. A coil type SMA wire connects the casing of the capsule on the end and work in antagonist way with the spring: when one SMA wire is not actuated the spring pushes the mechanism and open three legs, when it is actuated it pull the legs to stay closed along capsule body. Locomotion is performed by sequentially opening and closing the legs and elongating the central part of the robot in an inchworm-like strategy. Some preliminary tests inside a tube showed an average velocity of the prototype of 0.5mm/sec.

- In [15] a novel locomotion principle for endoscopic robot is presented, which is obtained simulating the motion of cilia conveying mucous layer. Activation of a single locomotion unit, made of two cilia, starts with both cilia closed, the following sequence of closing and opening cilia allows to produce a locomotion. The robotic capsule, produced in order to test this locomotion principle, is 35mm long and with a diameter of 15mm. On the robot there are six ciliated cells (each one has two cilia and is 15mm long, 5.2mm wide and 4.5mm high) which are embedded on capsule body together with the electronic boards useful for their actuation. The cilia are actuated through a two SMA springs which work in counter direction as antagonist muscles. First in-vitro tests performed showed a velocity of the robot of 24mm/min with a low efficiency, mainly due to the low number of cilia of this prototype.

The main advantage of an internal locomotion approach is that it is possible to achieve the adequate degree of flexibility and accuracy during the capsule journey [9]. The main drawback is that on board locomotion systems impose severe constraints in terms of size and power supply, so, this solution can show dramatic limitations in terms of power.

Figure 3.1 summarizes the two different approaches in the selection of a locomotion system for an endoscopic capsule. The internal locomotive strategy allows more flexible capsular endoscopes, have more complex design and have miniaturization skills. On the opposite, the external locomotive strategy gives rise to designs which are less flexible in motion, needs more bulky systems (outside the human body) but there is no need for miniaturization.

Based on a cost reduction and considering the performances that can be achieved with both locomotive systems, the more appropriate solution seems the internal locomotive strategy. With internal locomotion we can envisage further improvements adding intelligence to the capsule for smart movement.

Due to the differences in the environment depending on the district where the capsule is located, the issues to be addressed in order to achieve an effective locomotion or actuation may be drastically different. Nevertheless, if the locomotion system is carefully chosen, it will be possible to use the same driving system in all the GI regions. Therefore, a particular solution for each region is proposed [16].

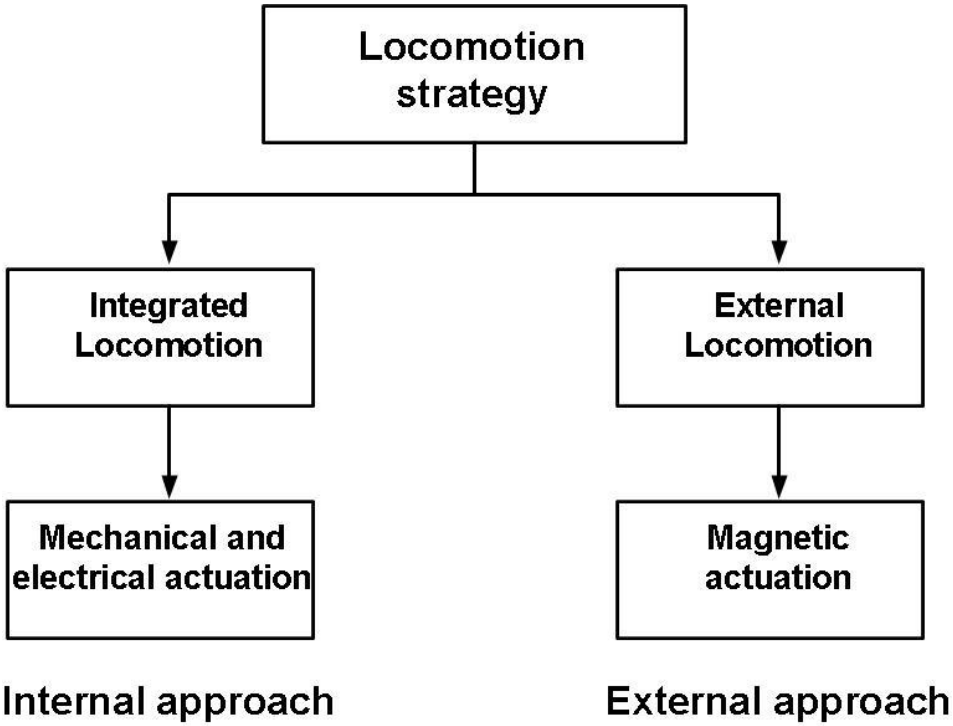


Figure 3.1: Diagram showing the two different approaches in the selection of a locomotion system for an endoscopic capsule.

- Esophagus: A capsule with a stopping mechanism or with a system to reduce the speed during swallowing would enable a reliable diagnosis of esophageal diseases [17].

- Stomach: Clinical evidence demonstrated that the patient's stomach can be filled with water without any significant perceived discomfort. The proposed strategy is an internal approach with the capsule equipped with one or more propellers, moving as a submarine in the stomach [18].

- Colon: Tissue distension (that is normally collapsed) could be mechanically performed by the legs, having multiple functions in addition to locomotion (e.g. tissue probing) [19].

The most restrictive solution is the legged locomotion because it requires the harmonic integration of two equally critical systems, respectively dedicated to achieve contact with the tissue so that locomotive forces can be transmitted, and to displace the contact points so that locomotion can be produced.

In legged locomotion the propulsion force must be large enough to enlarge the tissue collapsed over the capsule's body. A value of force needed for locomotion has been estimated thanks to a simulation based on the theoretical model described in [20]. The estimated elastic response in the colon is around 1 N/mm (which refers to the force given by the tissue per unit of width).The selected actuation system has to provide such propulsion force, has to be compact for not increasing the size of the capsule, low power, safe and bio compatible. For this reason, as concluded in [19] the best solution is to use a brushless dc (BLDC) micromotor. Figure 3.2 shows the overall design of the actuation system for activating a leg.

For simplicity, the esophagus region also will use a BLDC micromotor to enable the stopping mechanism. For the stomach, DC micromotors will be used to move the propellers. Nevertheless, it also possible to use other solutions to enable locomotion like Electro polymer actuators (EPAs) [21] or piezoelectric actuators [22]. Figure 3.3 shows the overall design of the actuation system for the locomotion in the esophagus and in the stomach.

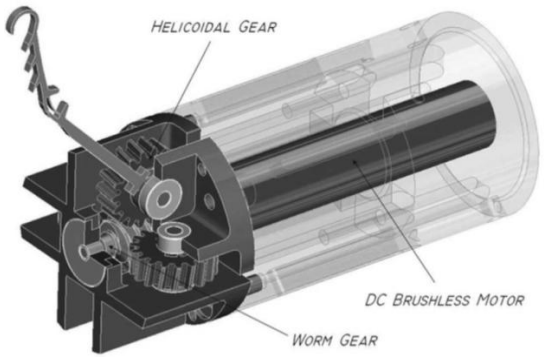


Figure 3.2: Overall design of the actuation system for activating a leg. Image taken from [19].

Figure 3.3: Overall design of the actuation system for the locomotion in the esophagus and in the stomach respectively. Images taken from [17] and [18].

3.2. Electronics for driving DC/BLDC motors

The chosen locomotive strategy relies on the use of DC and BLDC motors depending on the region under exploration of the GI tract. Typically, DC motors are controlled by an H-Bridge circuit [23] while BLDC motors are controlled using a 3-phase inverter [23,24]. Figure 3.4 shows the schematic of both drivers. From figure 3.4 it can be seen that the 3-phase inverter structure can be used to drive a DC motor if two inverters are connected to the DC motor and the other one is left floating.

The DC motor used for the locomotion in the stomach is the MK04S-24 from Didel. The BLDC motor used in the esophagus and the colon is the SBL04 micromotor from Namiki. Both motors work fed by current. The operating principle of a DC motor is simpler because the driver only has to supply current through one branch to the other. In contrast, there are different controlling methods to drive a BLDC motor [22-35]. In this chapter it is selected a six-step commutation with a 120 degree control [25] because it permits to use a sensorless control method. Figure 3.5 shows the 3-phase inverter driver connected to the electrical representation of a BLDC motor. The three-phase inverter is composed by 6 MOSFETs and controlled by 6 different signals [36]. Usually the MOSFETs are accompanied with a Schottky diode in anti-parallel in order to manage the current generated in the inductance of the motor when one of the driving transistors is switched-off. Basically, the diodes maintain the transistors in the safe operating are (SOA). The commutation phase sequence is like U+V- - U+W- - V+W- - V+U- - W+U- - W+V-. Therefore, only two phases conduct current at any time, leaving the third phase floating. The commutation phase sequence can be enabled using PWM signals or by simply using ON/OFF signals.

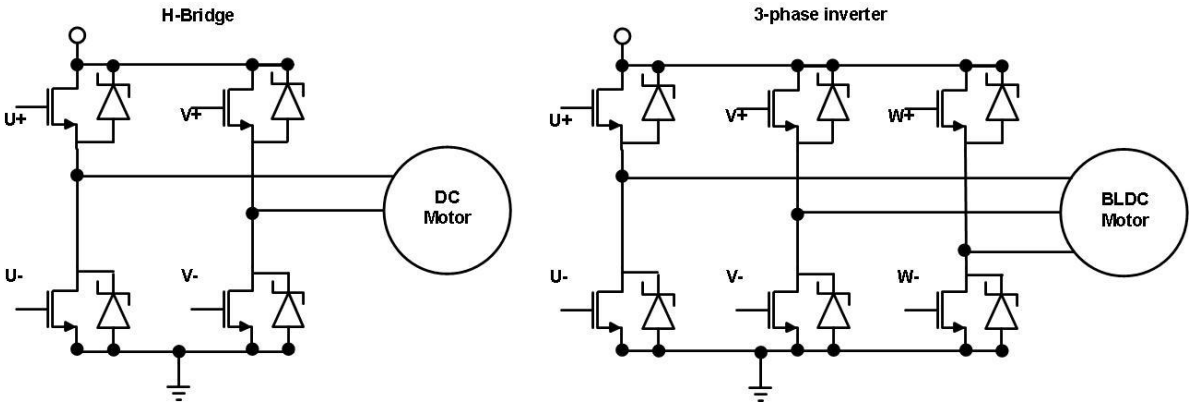


Figure 3.4: Schematic of the typical drivers used to drive a DC motor and a BLDC motor.

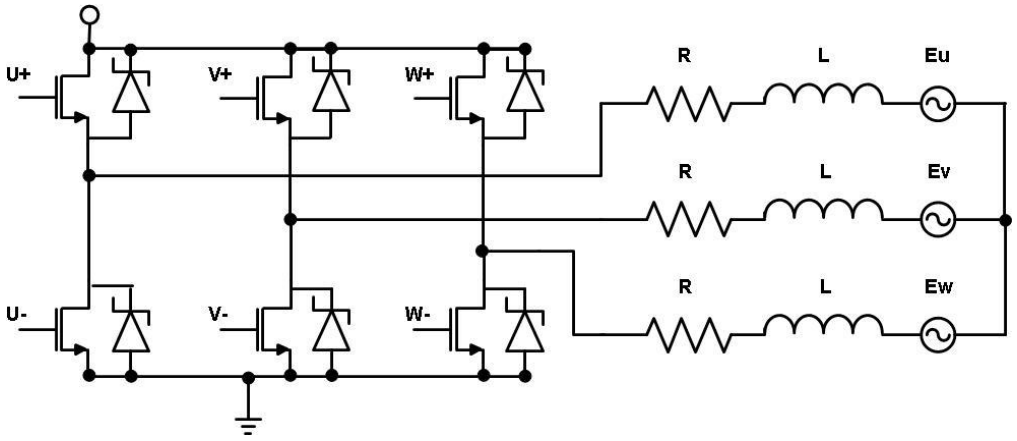


Figure 3.5: Schematic of the 3-phase inverter connected to the electrical model of the BLDC motor.

The commutation timing is determined by the rotor position, which can be determined using sensors like Hall sensors, resolvers or absolute position sensors, or using sensorless detecting methods [37]. The use of external sensors increase the cost and size of the motor, and sometimes they have some limitations, like being temperature sensitive [38]. There are different sensorless control techniques in the literature like [24-31]. In this chapter, the position of the rotor is determined by detecting the back electro motive force (BEMF) of the motor [37] because it is not dependent of the parameters of the motor.

Nevertheless, the miniaturization of the drivers to be included in a capsule endoscope imposes high spatial and electrical constraints that require special attention. The solution related to the miniaturization of the DC/BLDC driver is presented in section 3.2.1, and the design of the driver is presented in section 3.2.2.

3.2.1. Miniaturizing a DC/BLDC motor driver for a capsular endoscope

Many different circuits can be found in the literature to drive a BLDC motor [39-41]. However, the spatial constraints imposed by the capsular endoscope discard almost all the solutions. Moreover, these

solutions do not take care of the freewheeling currents, and this could be a problem in a battery powered device like a capsular endoscope. Therefore, it is clear that it is needed to design a solution which has to be able to dramatically reduce the area occupied by the motor driver and to eliminate or reduce the freewheeling currents.

3.2.1.1. Reduction of area

In [42] it is presented a driver for a BLDC motor to be used in a capsular endoscope. The proposed solution consists in using a discrete driver composed by 3 inverters of 3.2 mm x 3 mm each one and a control unit of 5 mm x 5mm to control them. Although such solution is integrated in a capsular device it requires a big amount of area. The solution proposed in this chapter consist in designing from the scratch an ASIC containing the driver and the controller of the DC/BLDC motor. With this strategy, the area occupied by the driver can be dramatically reduced because the driver and the controller only contain the minimum required circuits to move the motor.

The main issue of this solution is that the diodes connected in antiparallel. One solution is to integrate the diodes together with the transistors. In this case, the area occupied by the diodes is too large because the diodes have to be large enough to sustain the freewheeling current. Another solution is to design the 3-phase inverter driver without these diodes and to use off-the-shelf diodes, which requires even higher area than the previous solution. A better size reduction of the motor driver can be achieved eliminating the antiparallel diodes and to use the parasitic diodes of the transistors. In this case the transistors will not be in the SOA region if the freewheeling currents are not eliminated.

As a conclusion, to achieve the maximum integration and safety operate the 3-phase inverter it is necessary to eliminate the freewheeling currents.

3.2.1.2. Eliminating the freewheeling currents

The BLDC micromotors are electrical machines consisting of a rotor composed by permanent magnets and a stator where is arranged a number of stages. The rotor is made with rare-earth permanent magnets and is composed of a whole number of pairs of magnetic poles, and this number affects the relationship between the speed of a motor and the frequency of electrical control signals

The speed at maximum rotation of BLDC micromotor is a few thousands of rpm. For this reason the typical frequency of electrical control signals is ranging from a few Hz to few kHz. In this range of frequencies there are significant dissipative and inductive effects, and absolutely negligible capacitive effects between the coils of the motor. As it is shown in figure 3.6, the motor is represented as 3 branches between terminals U, V and W on the one hand and the neutral terminal N on the other. Each branch has a series resistance (Ru, Rv, Rw), and various terms that represent the derivative time of magnetic flux coupled with the windings of the phases:

An inductor (Lu, Lv, Lw), which takes into account changes in the current stage.

BEMF, Back Electro-Motive Force (Eu, Ev and Ew) induced in different phases of the stator by the rotor in motion.

The driver used for this motor is a 3-phase inverter. With this driver, the voltage in the branch is

$$V_x = V_n + IR_x + L_x \frac{dI_x}{dt} + E_x \qquad (1)$$

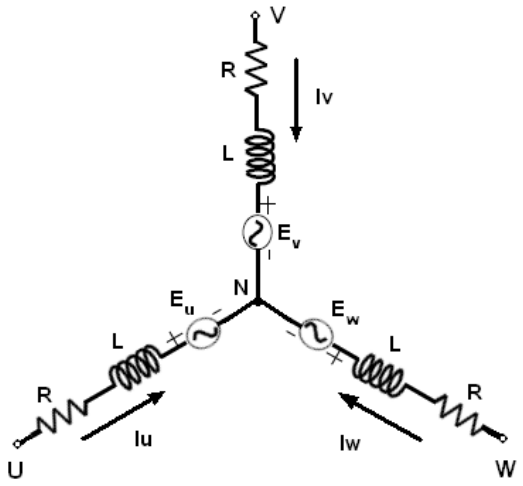


Figure 3.6: Equivalent circuit of a BLDC motor.

where x represents each of the branches of the motor (U, V and W). Using the law of Fadarday-Lenz, the BEMF is equal to the time derivative of the magnetic flux generated by the rotor.

$$E_x = -\frac{d\emptyset_x}{dt} \qquad (2)$$

Equation (1) shows the variation of voltage in an ideal case. As the intensity variation is not instantaneous, the variation of voltage is approximately

$$V_x \approx V_n + IR_x + L_x\frac{\Delta I_x}{\Delta t} - \frac{\Delta\emptyset_x}{\Delta t} \qquad (3)$$

As can be deduced from (3), when one phase is switched off, the increment/decrement of Vx becomes too large, because the increment of time is small. This sudden increment/decrement of electric charge in the branch of the motor is evacuated by the diodes of the 3-phase driver. The effect is called freewheeling current.

Typical values of Lx are around few micro H. Therefore

$$\left|L_x\frac{\Delta I_x}{\Delta t}\right| \ll \left|-\frac{\Delta\emptyset_x}{\Delta t}\right| \qquad (4)$$

From (3) and (4), it is deduced that the freewheeling currents are mainly produced by the variation of magnetic flux generated by the rotor.

There have been reported two different methods to avoid the use of the Schottky diodes used to drive the freewheeling currents. The first one consists in using the Synchronous Rectification (SR) control method [43,44]. The second one consists in controlling the induced freewheeling currents [45,46].

Synchronous Rectification strategy

The synchronous rectification (SR) method consists in to open the transistor which is connected in antiparallel with the diode responsible of driving the freewheeling current. Basically, such transistor must turn on few microseconds (in the order of 10 us) to drive the freewheeling current and to avoid generating a short circuit (with the other transistor of the inverter structure). The transistor will rest opened until it

pulls all the charge out (about 150 ns). Figure 3.7 shows the triggering signals to be applied for the SR method.

Although this method is used to eliminate the Schottky diodes, the SR method does not eliminate the freewheeling effect. Basically, the effect is minimized because the transistors need less voltage variation than the diodes to pull the charge out of the motor winding.

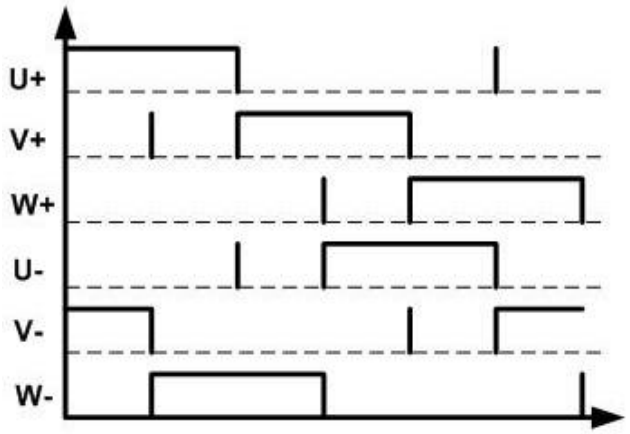


Figure 3.7: Triggering signals for the SR method

Controlling the induced freewheeling currents

There are two possibilities to reduce the freewheeling currents. On the one hand, reducing the magnetic flux, the freewheeling currents are also reduced. However, the only way to change the magnetic flux is to change the motor. On the other hand, increasing the t the effect of the magnetic flux is reduced and, the freewheeling currents are also reduced.

Hence, the most suitable solution is to increase the t because it can be easily achieved by increasing the switching off time of the transistors, and the switching off time can be controlled by a digital controller or by an analog driver. In conclusion, this strategy reduces the value of Vx. With a lower Vx, the diodes of the 3-phases inverter never switch on and there are not any freewheeling current going from the motor to the supply.

In addition, the low speed of the micromotors is an advantage for this strategy because it permits to increase the switching off time without affecting the behavior of the micromotor. The worst case for this strategy is when the motor is working at the maximum speed, because the time while the transistors are switching off and the time while the transistors remain switched on can be comparable. If those times are comparable, the micromotor will not work properly even reaching the situation where the micromotor will not work.

3.2.2. Design of a 3-phase inverter in the 0.35 um HV technology from AMS

The 3-phase structure can be implemented in different ways:

- Architectures based on only nMOS transistors, which are more robust to latch up.

- Architectures based on nMOS and pMOS transistors. In this case it is easy to use the complete biasing range/voltage without applying voltages at the gate higher than the polarization voltage.

In the 0.35 um HV technology from AMS there is the possibility to use a wide variety of transistors, which are capable to operate at different voltages. Therefore different structures can be used. The proposed structures are presented in figure 3.8.

In (a) nmos/pmos transistors are substrate-based transistors operated at 3.3 V. These are the type of transistors of the technology providing lower Ron resistance and hence that can drive the motor with a smaller area of silicon. When one of the transistors of the driving phase is switched-off (for example nMOS 5 in figure 3.3), the voltage in the driving node is increased above 3.6 V (arrives up to 4 V) if external diode is not used and the driver enters in the non-safety region of operation. To avoid this, an external diode has to be used. Moreover, the diode must have a threshold voltage lower than 0.3 V to maintain the transistors in the safety operation region. In order to minimize the space required for the driver (taking into account the external components) this solution is discarded. The structure presented in (b) is composed of nmosim/pmosim transistors operated at a maximum voltage of 5.5V. As the transistors can operate up to 5.5 V they will never go into the non-safety region of operation. These transistors are not substrate based because they are isolated from the substrate with a well. Isolated transistors will induce less current into the substrate reducing noise. They have a lower Ron than the High-Voltage (HV) transistors. The structure in (c) is only based in nmosim transistors in order to have more robustness to latch up. Finally, the structure in (d) is formed by HV nMOS transistors (NMOS50H). As it is a nMOS-only structure it is expected to be more robust to latch up as well. Moreover, the 50 V capability makes this structure more robust also to voltage spikes. One of the problems with this structure is that the transistors have higher Ron compared with the low-voltage transistors (which implies higher area for the same current and higher driving voltages). Another drawback appears when the parasitic diode is used as the freewheeling diode. According to the simulations the voltage at the motor increases up to 10 V. To avoid this problem a NMOS50H transistor used as a diode is connected at the output, and it takes the current delivered by the inductance of the motor and eliminates the voltages spikes. Other HV structures have been discarded because they present similar problems like the nmos50h structure. In this case, it is more suitable to use low voltage transistors to design the 3-phase inverter driver.

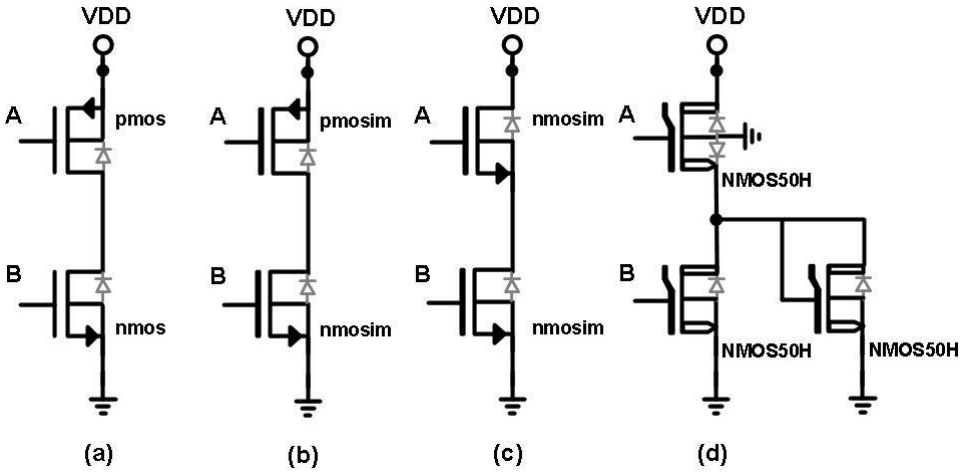


Figure 3.8: Analyzed architectures for the 3-phase driver.

Although it seems that the best structure is the shown in (b) or (c), the robustness of the structure in (d) to high-voltages spikes makes valuable the study taking into account that the good behaviour of the driver is based in the use of the parasitic diodes as freewheeling diodes (at least during a short time). Using HV pMOS devices on the high voltage side of the driver is not convenient because to increase the Vgs voltage and provide the required current, the polarization voltage has to be higher than 3.3V (the total power, VDD*I, would increase).

Figures 3.9, 3.10 and 3.11 show the current obtained in the 3-phase driver structure depending on the width of the transistor for different gate voltages and for each of the architectures presented. As expected it is observed that larger MOSFETS are required when using the NMOS50H solution. In this case the driving is not possible without increasing the gate voltage at least to 9-12V.

These graphs are used to know if it is possible to obtain 100 mA from the driver and to know which transistor size and gate voltage have to be used to obtain it. Comparing these three figures, it is clear that the most suitable structure to be used to design the 3-phase inverter is the nmosim/nmosim structure because it is the less area consuming. Although it is needed to apply 5 V at the gate of the nmosim transistor the width of the transistors has to be 5 mm instead of 10 mm in the pmosim/nmosim structure or 16 mm in the nmos50h structure. Therefore it is clear that an important size reduction is achieved by shifting the control signal up to 5 V and using the nmosim/nmosim structure.

The 3-phase inverter has to be complemented with a charge pump and some level-shifters in order to control the gate voltage applied to the nmosim/nmosim structure. Figure 3.12 presents the architecture needed for the driving of the motors. The charge pump generates up to 5 V and the level-shifter adapt the controlling digital signals from the level 0 - 3.3 V to the level 0 - 5 V. However, depending on the controlling strategy, using SR or controlling the induced freewheeling current, the drivers use different level-shifters.

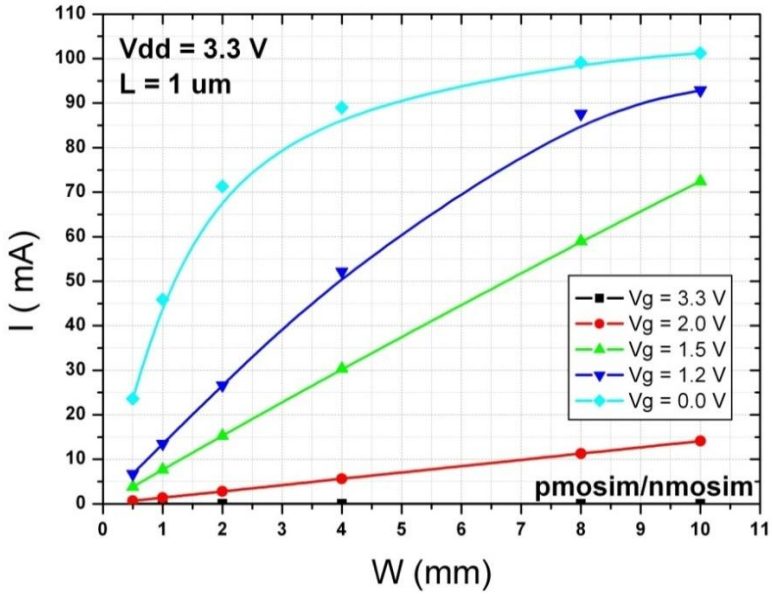


Figure 3.9: Current obtained for the pmosim/nmosim structrure depending on the width of the transistors. The Vg represents the voltage at the gate of a pmosim transistor.

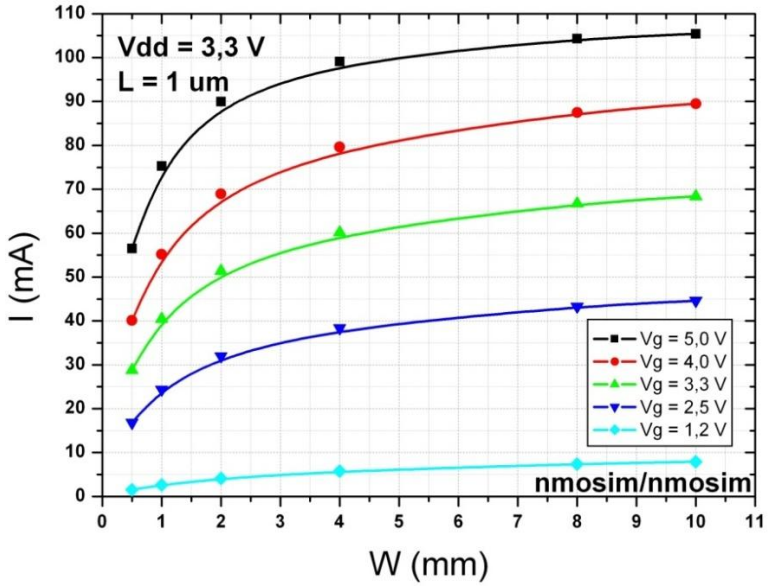


Figure 3.10: Current obtained for the nmosim/nmosim structrure depending on the width of the transistors. The Vg represents the voltage at the gate of a nmosim transistor.

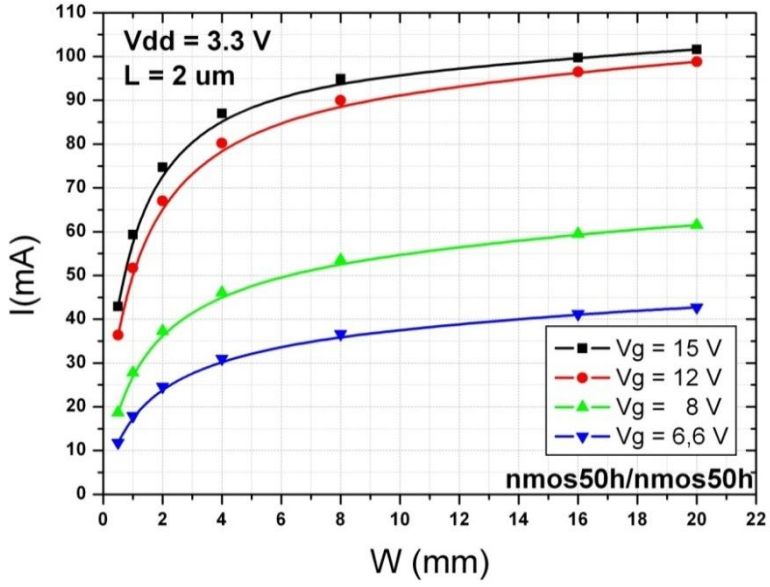


Figure 3.11: Current obtained for the nmos50h/nmos50h structure depending on the width of the transistors. The Vg represents the voltage at the gate of an nmos50h transistor.

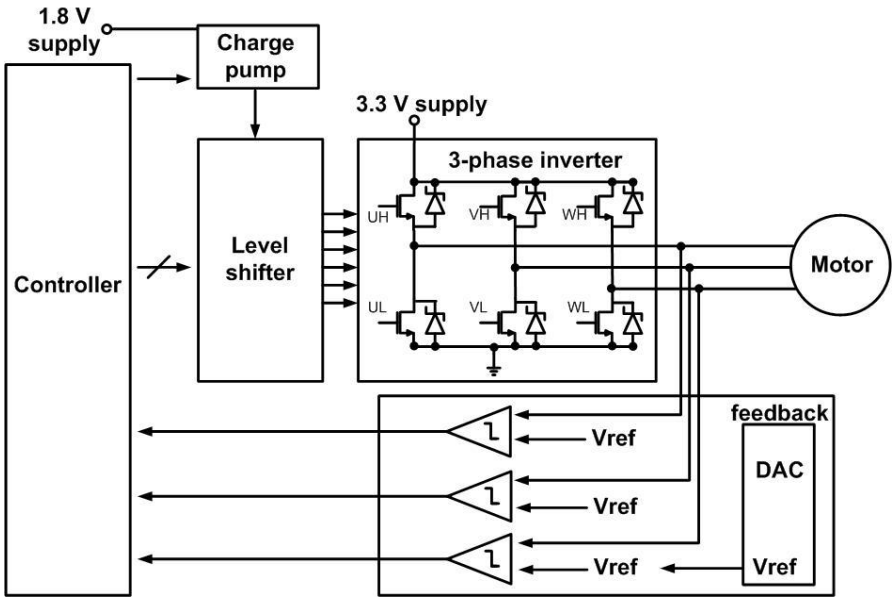


Figure 3.12: Architecture of the motor driver.

The charge pump is based on the Dickson charge pump [47] (Figure 3.13). Table 3.1 presents the size of the transistors of the charge pump presented in figure 3.13. It is designed for low voltage applications and has low power consumption. To generate any supply signal from 0 to 5 V, the charge pump must be supplied with an external voltage between 0.6 V and 1.8 V. The maximum power consumption is achieved when it is supplied by 1.8 V (an output of 5 V) and it is of 0.45 mW.

The driver has also a feedback stage to perform a sensorless control based on the measurement of the back electromotive force (BEMF) generated at the motor. The feedback stage is composed by three comparators and a R-2R digital to analog converter (DAC). Each comparator senses each motor phase. The DAC generates the voltage reference for the comparators.

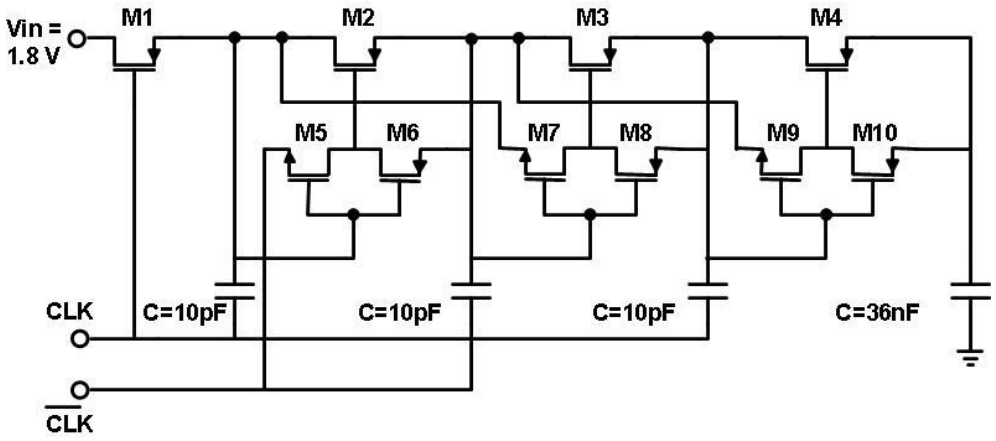


Figure 3.13: Schematic of the charge pump.

Table 3.1: Size and type of the transistors used in the charge pump.

Transistor	Type	W (um)	L (um)
M1 – M4	Pmos	13	8
M5, M7, M9	Pmos	0.8	6
M6, M8, M10	Nmos	0.8	0.35

Finally, in normal operation, the driver is programmed with a 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 afterwards 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 [37]. The start-up sequence is included in the FSM used to control the driver.

3.2.2.1. Practical application of the Synchronous Rectification strategy

In order to apply the SR method in the DC/BLDC motor driver presented in figure 3.12 the controller has to be capable of reproducing the control signals presented in figure 3.7. The SR control method generates signals of 150 ns which have to be shifted using level shifters (figure 3.12) in order to reduce the size of the driver. To properly maintain the correct operation of the driver, these level shifters have to be capable to drive the faster signals (150 ns).

The implemented level-shifters are similar to the used in [48,49]. Figure 3.14 shows the schematic of the level-shifter. Table 3.2 shows the size and type of the transistors used in the level-shifter. The principal property of this level-shifter is that it has no static power consumption. In addition, the level-shifters are able to manage different gate-source voltages by changing their supply. All these level-shifters are powered by the charge pump presented in the previous section.

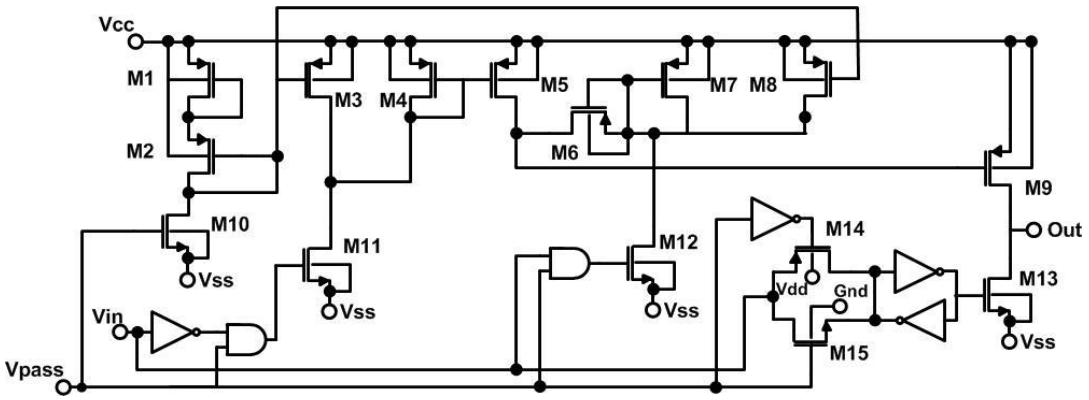


Figure 3.14: Schematic of level shifter.

Table 3.2: Size and type of the transistors used in the level-shifter.

Transistor	Type	W (um)	L (um)
M1	Pmosim	2	1
M2	Pmosim	2	1
M3	Pmosim	2	1
M4	Pmosim	1	1
M5	Pmosim	1	1
M6	Pmosim	20	3
M7	Pmosim	2.5	1
M8	Pmosim	2.5	1
M9	Pmosim	400	1
M10	Nmosim	201	1
M11	Nmosim	5	1
M12	Nmosim	4.95	1
M13	Nmosim	22.2	1
M14	Pmosi	10	0.7
M15	Nmosi	10	0.7

3.2.2.2. Driving signals for low freewheeling current operation

The freewheeling currents can be reduced by controlling the switch off time of the transistors. With this strategy, the transistors of the 3-phase structure have to be switched on/off slow enough to reduce the effect of the magnetic flux on the driver. Accordingly to the simulations, 30 us is slow enough to almost eliminate the freewheeling current. This strategy can be implemented in two different ways:

- Using a digital controller and a Digital to Analog Converter (DAC) to drive the gate of the transistors. With this circuit it is possible to apply different voltage ladders that permit to switch off the transistors with different speeds.

- Using a level-shifter to drive the gate of the transistors. Depending on the rise/fall time of the level-shifter the transistors of the 3-phase inverter will switch off with different speeds.

The simpler solution is to use the level-shifters because it requires less area. The level shifters are specifically designed to drive the 3-phase inverter with and output signal with a rise/fall time of 30 us. Figure 3.15 shows the schematic of the level-shifter. Table 3.3 presents the size and type of the transistors used in the level-shifter.

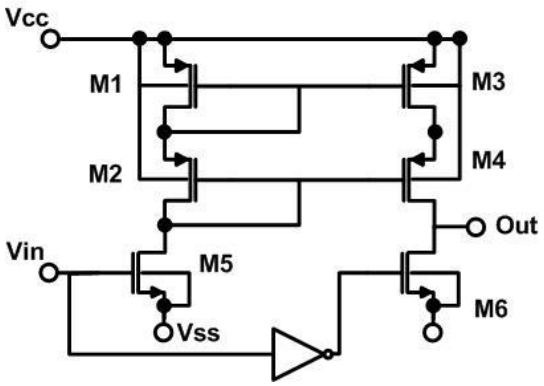


Figure 3.15: Simplified Schematic of the level shifter.

Table 3.3: Size and type of the transistors used in the level-shifter.

Transistor	Type	W (um)	L (um)
M1	Pmosim	2	10
M2	Pmosim	2	10
M3	Pmosim	2	10
M4	Pmosim	2	10
M5	Nmosim	0.5	10
M6	Nmos50h	10	12

Finally, the complete driver used to control the freewheeling currents is the same as presented in figure 3.12. The driver is very similar to the driver using the SR method. It uses the same charge pump to generate up to 5 V and it uses level-shifters to adapt the controlling signals. However, in this case the level-shifters are different.

3.2.3. Implementation results

A DC/BLDC motor driver with the SR control method and a driver with the control of the freewheeling currents have been designed and fabricated in the 0.35 um HV technology from AMS. In order to study the behavior of 3-phase inverter structure in this technology and to study the two presented control methods two different ASICs have been designed and fabricated at the same time. The first one includes several drivers and structures to study the technology and the behavior of each circuit. The second ASIC is shown in figure 3.16.

The ASIC includes two DC/BLDC motor drivers (one using the SR method and the one using the control method to control the freewheeling currents). A liquid lens is also included. Each of the motor drivers is highlighted. The ASIC is 3 mm x 2.7 mm and it also one liquid lens driver (described in chapter 4).

The test of both drivers has been done using the SBL04 BLDC motor from Namiki. This test has demonstrated that the drivers can operate without the need of external diodes. When using the SR control method the Schottky external diodes are not needed because the freewheeling currents are driven by the

transistors. Thus, with the SR driver are obtained the same results than using the typical driver. The only difference is that the voltage drop due to the freewheeling currents is lower because these currents are pulled out by the transistors.

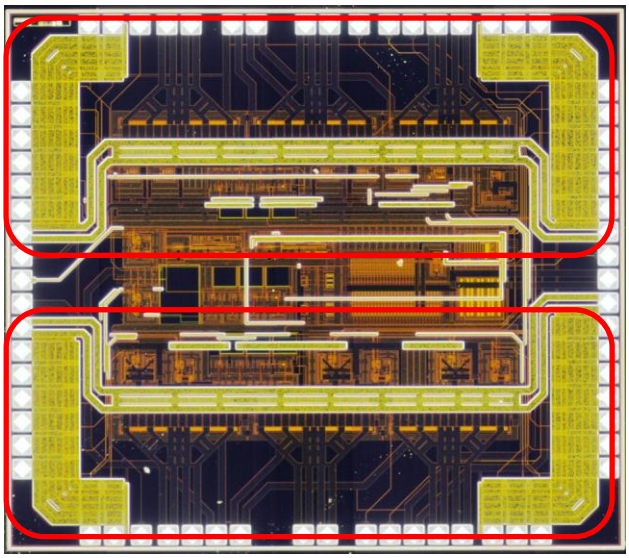


Figure 3.16: Photography of the fabricated ASIC of 3 x 2.7 mm^2. The two motor drivers are highlighted.

The start-up process applied to the BLDC motor is shown in figure 3.17. It consists in aligning the rotor in 12 steps. Once the rotor is aligned it is possible to detect the BEMF signal, and then it is possible to control the BLDC motor.

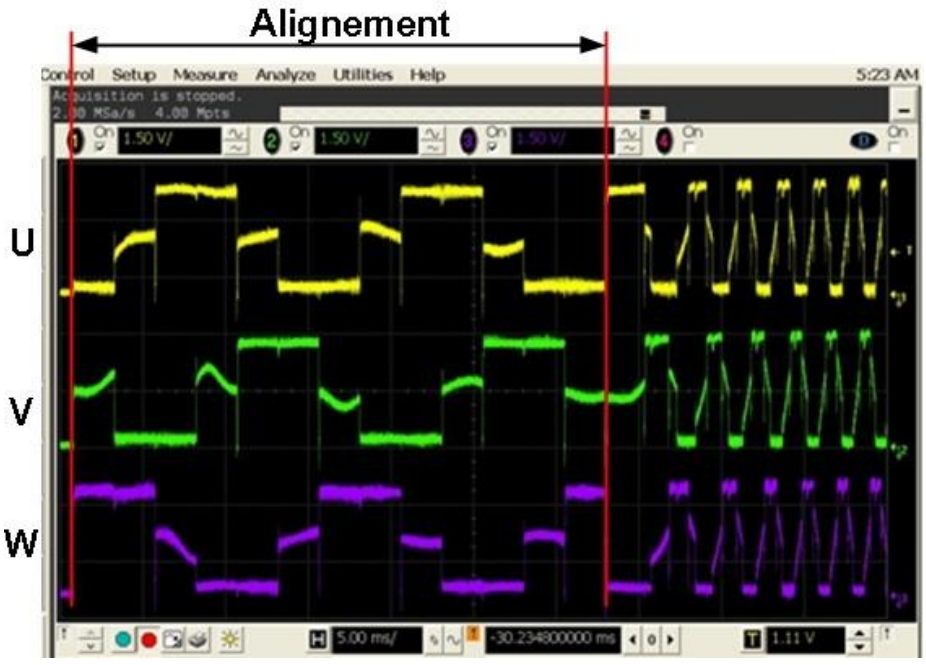
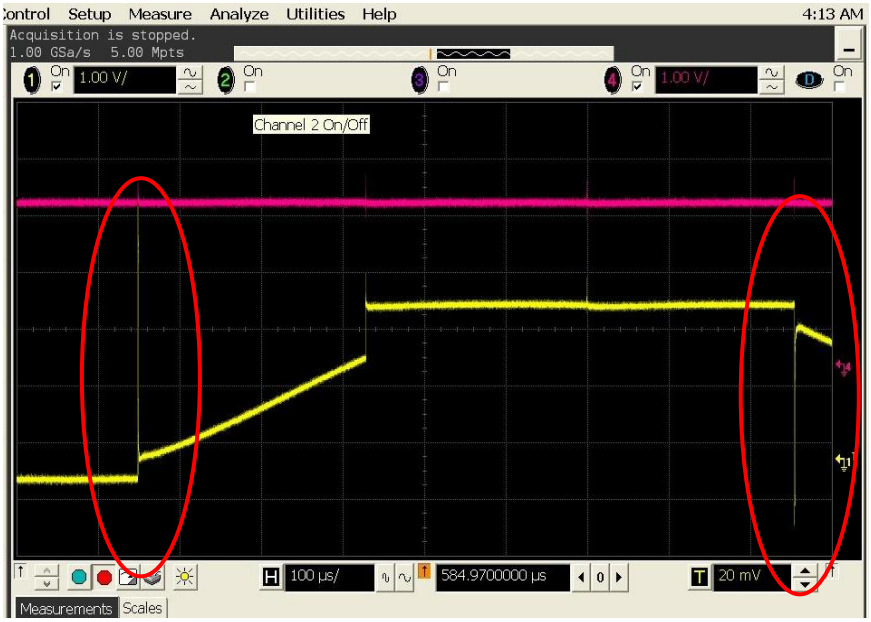


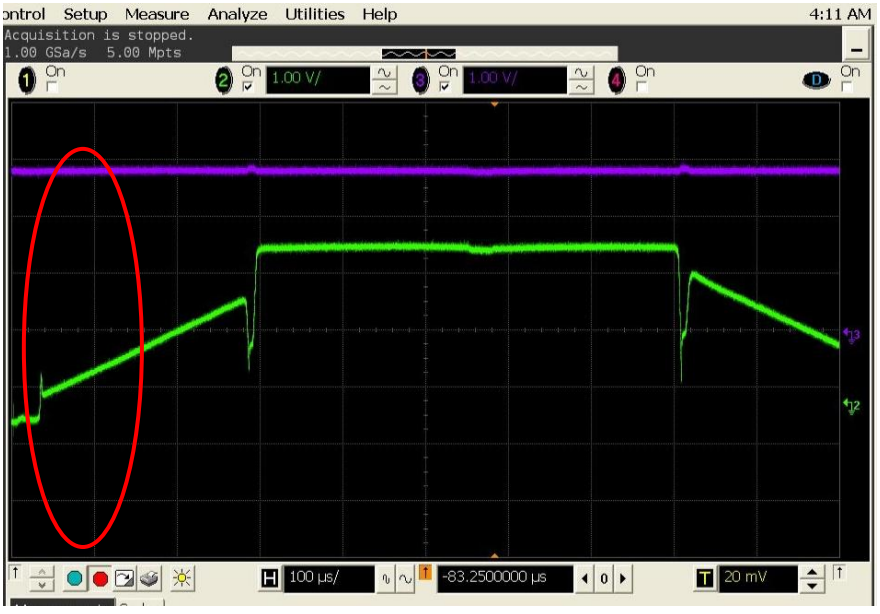
Figure 3.17: Start-up of the BLDC motor using 12 steps to align the rotor.

Figure 3.18 shows a comparison between a normal driver (using external diodes) and the designed DC/BLDC driver controlling the freewheeling currents. In figure 3.18a, it can be seen the effect of the freewheeling currents in the voltage measured in a motor winding. In comparison with figure 3.18b, it can

be seen that the presented driver is capable of eliminating the major part of the freewheeling currents (rounded with a red line) while working in a low speed mode. In contrast, it can be seen that some glitches appears because the controller uses more time to change from one state to another.



(a)



(b)

Figure 3.18: This figure shows the supply signal and the output signal of the drivers (a) Driver with freewheeling currents and (b) Driver without freewheeling currents.

Finally, the area occupied by each driver is presented in Table 3.4. As can be seen, the SR driver and the driver without freewheeling currents are the less space consuming and the most suitable to be

integrated in an endoscopic capsule. Therefore, a significant area reduction has been accomplished by including the DC/BLDC in a specially designed ASIC.

Table 3.4: Area occupied by different drivers.

Methods			
Off-the-shelf driver	**Driver with external diodes**	**Driver with SR**	**Driver without freewheeling currents**
Driver 3.2x3 mm2 (x3)	Driver 2x0.7 mm2	Driver 2x0.7 mm2	Driver 2x0.7 mm2
	Diodes 0.6x0.8 mm2 (x6)	Capacitor 1x0.5 mm2	Capacitor 1x0.5 mm2
	Capacitor 1x0.5 mm2		

3.3. Conclusions

The need of improving the diagnosis in capsular endoscopy has brought to include active locomotion as a basic function in the capsule. Typical capsular endoscopes move passively (i.e. by peristalsis) and when one region has been explored there is no way to return back or stop the capsule to get more details about the region under study. In contrast, active locomotion allows the system to be moved forward and backward and also to be stopped, which permits to study in more details certain regions and permits to move quickly in regions without interest.

In this chapter, internal and external approaches to active locomotion have been discussed. Although the external approach is working in some capsule prototypes, the internal approach is more cost effective and allows further improvements by adding intelligence to the capsule. Moreover, as implemented in this work, allows robotic capabilities on board which is necessary for further improvements of the endoscopes. To solve the problem of the different regions of the GI the endoscope robot uses 3 different locomotive strategies depending on the region under study: esophagus, stomach or colon. Nevertheless it has been possible to design a unique ASIC that will cover all regions. Different actuators and motor type (DC or BLDC) are used in different regions of the tract.

The spatial constraints imposed by the low area available inside a capsule has brought to integrate 2 motor drivers in a single ASIC. The first motor driving uses the SR driving strategy. The second driver uses new driving strategy consisting into reducing the freewheeling currents. The area occupied by each driver is the same (2 mm x 0.7 mm), both drivers avoid the use of external diodes and both drivers only need to use an external capacitor.

The area reduction of the presented drivers compared to an off-the-shelf driver is about 90 %.

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4. Enabling advanced vision functions in active capsular endoscopy

Acquiring good images of the GI tract in traditional endoscopy is the most important function for the diagnosis of the patient. However, when miniaturizing to capsular endoscopy, the available power and the available space impose very high constraints in the imaging function. Therefore the frame rate and image quality are reduced in comparison to traditional endoscopy. Typically, capsular endoscopes acquire images at 2 fps with VGA resolution while traditional endoscopes acquire images in real time and high definition (HD) resolution [1].

Active capsular endoscopy is a painless procedure which permits to explore the entire GI, stopping or accelerating the endoscope as required by the examiner. In this scenario, images obtained by the vision system become more important either for the purpose of diagnostics or for autonomous locomotion of the capsule, e.g. facing the lumen or holding a given position against the natural bowel movements [2]. In active capsular endoscopy the implementation of advanced vision functions like autofocus and zoom functions becomes more relevant, because it is possible to obtain more detailed images of the regions of interest [3-5]. [3,4,5]

Usually focusing and zoom functions are enabled using a group of optical lenses and at least one actuator used to modify the lens position. Actuators like brushless (BLDC), stepper or coil motors are typically used [3-5] but they require too much volume to fit in a capsular endoscope. Other approaches consist in using microlens with pneumatic [6], piezoelectric [7] or thermal actuation [8] or using liquid lens [9,10].

The aim of this chapter is to present the system needed to enable advanced functions in capsular endoscopy. In particular, a liquid lens is selected as the actuator for the vision system. It is described in section 4.1. The electronics needed to drive such liquid lens are described in section 4.2. Finally the results and the conclusions are presented in section 4.3 and 4.4 respectively.

4.1. Liquid lens

Compared to other methods to change the focal of the optical system, the liquid lens solution presents some advantages. The focal is not changed mechanically, it is changed by applying a specific voltage. In addition, liquid lenses have a fast response, are low cost, low power and have a small size.

Basically, in a liquid lenses, the change of the focal is due to the change of the curvature of the liquid lens. Depending on the way to achieve such curvature, it is possible to find several types of liquid lens. For example, in [11] a fluidic adaptive lens is presented. It has been inspired by animal eyes crystalline lenses that can be deformed by muscles to adjust their focal length. Figure 4.1 illustrates the process. Basically, this liquid lens is composed by two different transparent liquids. The liquids are stored in different chambers separated by a membrane. One of the liquid chambers is connected to a syringe pump through the fluidic inlet. When pressure is applied by the syringe pump to inject fluid into the lens chamber, the focal length of the lens changes because of the elastic deformation of the membrane. Similar implementations have been used by others research groups, like in [12].

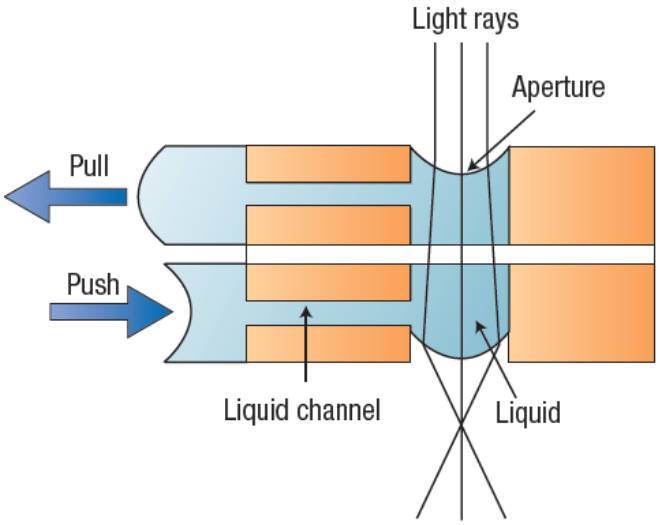

Figure 4.1: Focusing system for a liquid lens proposed by [**11**].

The most common liquid lenses use the electrowetting process in order to change its focal. These liquid lenses also use two different transparent liquids, one is insulating and non-polar and the other is a conducting water solution. When a voltage is applied, the conducting liquid is deformed and then the focal length is changed. Commercially available liquid lenses using the electrowetting process can be obtained for example in Varioptic. Figure 4.2 shows the focusing system for the liquid lens from Varioptic [13,14]. Other vendor of similar lenses is Phillips Electronics. Figure 4.3 illustrates the focusing process for the liquid lens from Phillips.

In particular, the liquid lens used in VECTOR uses the electrowetting process because is more robust than the fluidic adaptive strategy. In this chapter, it is presented a liquid lens driver used to drive the ARCTIC 416 liquid lens from Varioptic. The lens from Varioptic uses two different electrodes to apply the driving signal. This liquid lens can be modelled as a resistor with a capacitor in series between each electrode. The working principle is simple, the focal of the lens is changed when it is driven with a PWM signal of amplitude between 30 V and 60 V. The driving frequency of the liquid lens is 1 kHz (from datasheet) and the capacitance of the lens in this case is 150 pF. Figure 4.4 shows how the focal of the lens is changed depending on the applied voltage (Vrms).

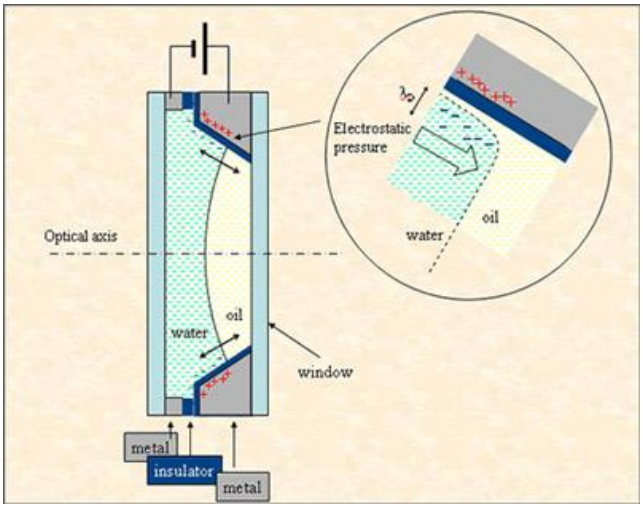

Figure 4.2: Focusing system for the líquid lens from Varioptic. It uses the Electrowetting process to change the focal.

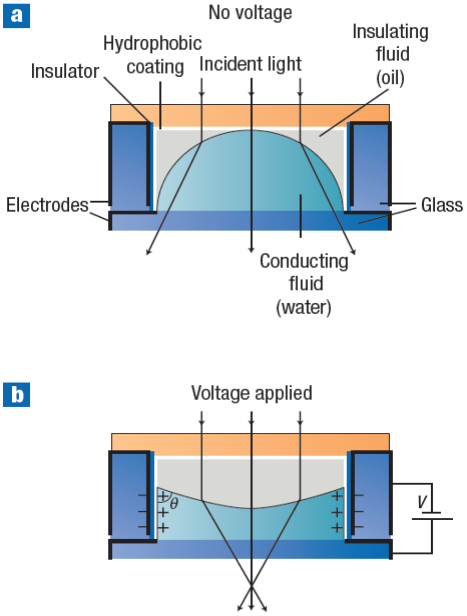

Figure 4.3: Focusing system for the liquid lens from Phillips. It also uses electrowetting: a) concave diverging lens b) convex converging lens

4.2. A liquid lens driver for integration in a control chip for capsule endoscopy

The 416 ARCTIC liquid lens is a commercial solution, for this reason it is possible to find out different drivers in the market [15-17]. Drivers usually include at least a DC-DC converter to generate high voltages and an H-Bridge (HB) to drive the liquid lens. Off-the-shelf components are also required to assure the correct operation of the driver.

Although the available drivers work properly, they would consume too much area inside a capsular endoscope. Thus, the proposed solution is to include a liquid lens driver in the control ASIC presented in chapter 2. This solution only requires adding some additional registers to the ASIC to control the liquid

lens, and it also requires using a bit more area to add the driver. Nevertheless, the increase in area is much lower than using a commercial driver.

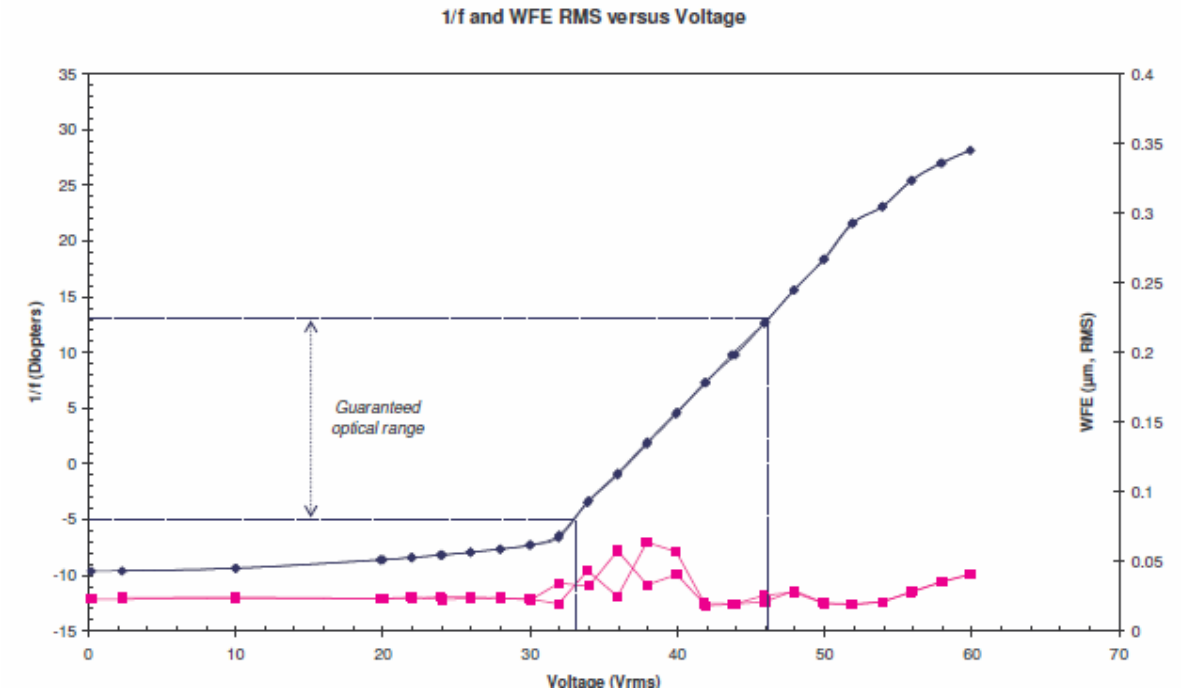

Figure 4.4: 1/f versus the applied voltage at the liquid lens.

By similarity with the other drivers an HB driver [18] is used to drive the liquid lens. The high voltages needed by the liquid lens are also generated internally to minimize the number of external components required. Figure 4.5 shows the overall architecture of the liquid lens driver.

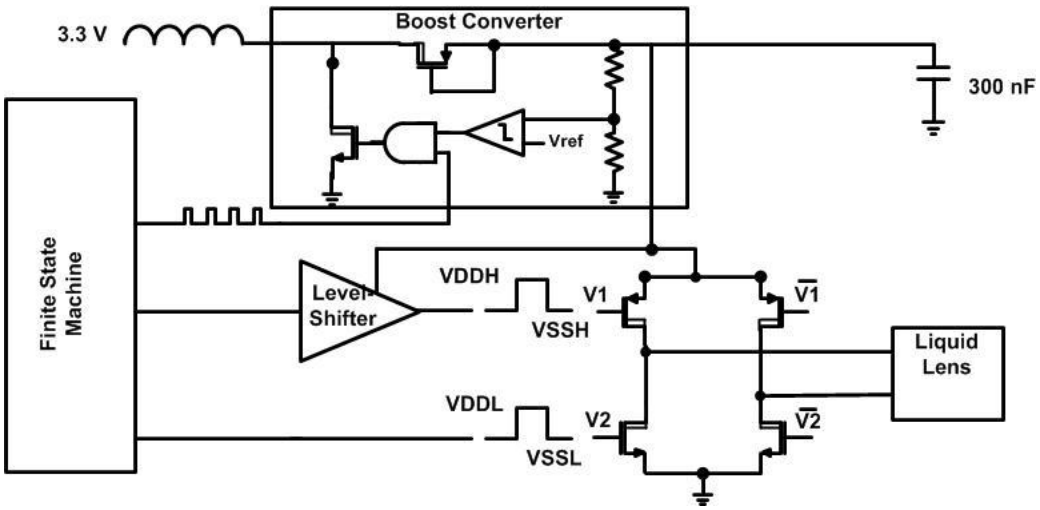

Figure 4.5: Overall architecture of the liquid lens driver.

The inductor and the output capacitor are external components because they integration require too much area. The main element of the lens driver is an 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. The High Voltage level-shifters are needed to raise the driving signals to the operating gate voltages of the HV-PMOS transistors. Thus, the HV-PMOS transistors of the HB are driven with signal from VDDH to VDDH – 2 VTHP (where VTHP is the threshold voltage of the HV-PMOS transistor). Under normal operation the driver 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 control of the driver is performed by a FSM which is also included in the design. A more detailed description of each circuit is given next.

4.2.1. DC-DC boost converter

A DC-DC boost converter is a device that accepts a DC input voltage and produces a DC output voltage. The output produced is higher than the input voltage. DC-DC boost converters are widely used, for example in different applications like providing noise insulation, the regulation of power buses, etc.

Figure 4.6 shows the schematic of a basic standard boost converter, which only needs five elements: an inductor, a diode, a transistor, a capacitor and a load.

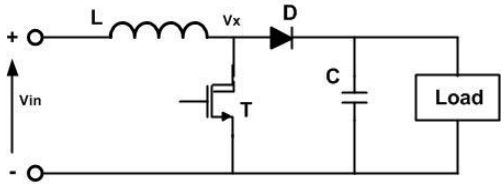

Figure 4.6: Simplified schematic of a DC-DC converter.

Basically, the boost converter has two operating modes or states depending if the switch is ON or OFF. When the transistor is switched ON, the rising input current flows through the inductor and the transistor. When the transistor is switched OFF, the current which was flowing through the transistor would now flow through the inductor, the capacitor, the load and the diode. The inductor current falls until the transistor is turned on again [18,19]. The energy stored in inductor L is transferred to the load. Figure 4.7 presents the equivalent circuits for these operation modes.

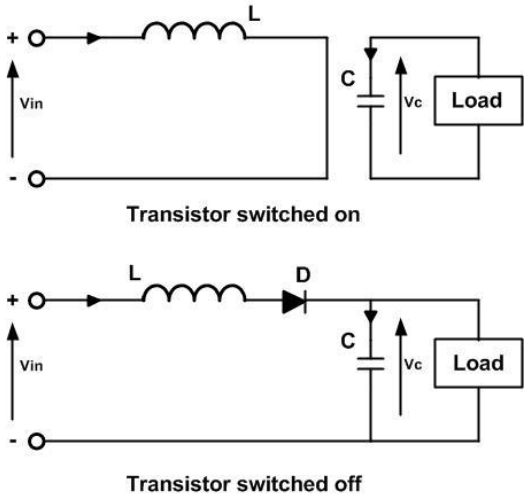

Figure 4.7: Equivalent circuits for the two different operating modes.

When the energy required by the output load is high enough, the boost converter has to be transferring power from the source to the output continuously, which basically means that the current through the inductor never falls to zero. In this case, the boost converter is working in continuous load current mode. When the energy required by the output load is low enough, the energy stored in the inductor can be rapidly transferred to the output load and then, the inductor current falls to zero during the rest of the period. In this case the boost converter is working in discontinuous load current. Figure 4.8 shows the waveforms for voltages and currents with a continuous load current.

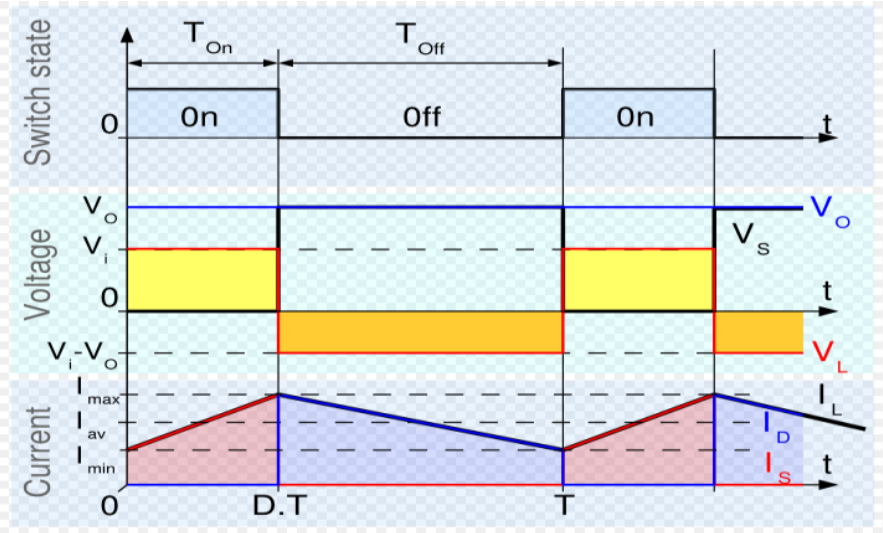

Figure 4.8: Voltage and current waveforms of a DC –DC boost converter working in continuous mode.

When the transistor is switched on the current raises from I_{min} to I_{max} in time DT, where T is the period of the switching signal and D is the duty cycle, and represents the fraction of time that the transistor is switched on, i.e. the value must be between 0 (the transistor is never off) and 1 (the transistor is always on). Assuming that the inductor current raises linearly the increment of current is:

$$\Delta I = \frac{V_S\, D\, T}{L} \qquad (1)$$

where T is the period of the signal applied to the transistor and L is the inductance. Assuming that when the transistor is switched off the inductor current falls linearly from I_{max} to I_{min}:

$$\Delta I = \frac{(V_{out} - V_S)\,(1-D)T}{L} \qquad (2)$$

Equating the two equations,

$$\frac{V_{out}}{V_s} = \frac{1}{1-D} \qquad (3)$$

The average inductor current can be ideally found out by equating the power drawn from the source to the power delivered to the load resistor. The power P_o absorbed by a load resistor R is:

$$P_o = \frac{(V_S)^2}{R} \qquad (4)$$

It can be seen from the circuit in Fig. 4.7 that the current drawn from the source flows through the inductor. Hence the average value of inductor current is also the average value of source current. With the average current being IL, the power PS supplied by the source is then:

$$P_S = V_s \times I_L \qquad (5)$$

After equating equations (4) and (5), we get the average inductor current as:

$$I_L = \frac{(V_o)^2}{V_s \times R} \qquad (6)$$

Since load current Io is:

$$I_o = \frac{V_o}{R} \qquad (7)$$

Using equations (3) and (7), equation (6) can be re-presented as:

$$I_L = \frac{I_o}{1-D} \qquad (8)$$

Since $0 < D < 1$, it can be seen from equation (17) that $I_L > I_o$.

Figure 4.9 shows the waveforms for voltages and currents with a discontinuous load current.

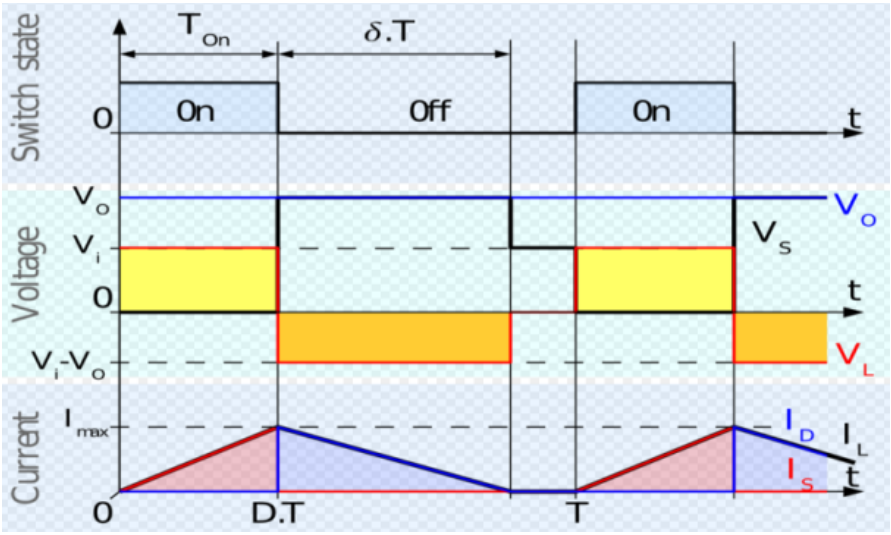

Figure 4.9: Voltage and current waveforms of a DC –DC boost converter working in discontinuous mode.

In this case, the relation between output and input voltages is,

$$\frac{V_{out}}{V_s} = 1 + \frac{V_s\ D^2\ T}{2L\ I_{out}} \qquad (4)$$

where I_{out} is the output current. Compared with equation (3), this expression becomes more complicated because it also depends of the input voltage, the inductor, the period and the output current.

The boost converter used in the liquid lens driver has to supply less than 1 mA to the HB and the level-shifters. Therefore, as the energy required in the output could be as great as 50 mW, the boost

converter needs to work in continuous load current mode in order to supply as much energy as possible to the output. Hence, as a first approximation, it is possible to evaluate the value of the duty cycle using equation (3). With this expression, the duty cycle of the signal applied to the transistor has to be 0.934. It means that the 93.4 % of the time the transistor has to be switched off, while the rest of time has to be switched on.

This approximated value of the duty cycle is needed to fix the period of the signal applied to the transistor. Such period has to be low enough in order to maintain the output capacitor charged and the output current constant. However, the lower the period is the higher the power consumption of the controller. Therefore it is needed to find a trade-off between both situations in order to minimize the power consumption as much as possible. For this reason, although the clock of the system works at 10 MHz (0,1 us) the period of the signal applied to the transistor is selected to be 4 us.

The value of the inductor is determined basically by the space constraints imposed by the limited space in the capsular endoscopic device. The boost converter forms part of a circuit used to drive a liquid lens in an endoscopic capsular robot. As the inductor to be used is an external device (it is not implemented in the ASIC), the chosen inductor is the one which occupies less space. For this reason, it is used a SMD inductor of 220 uH.

Finally, the value of the output capacitor has been found using the simulations. As it is desired a constant output current less than 1 mA, the capacitor needed to maintain the output stable is 300 nF. As this capacitor requires too much area to be integrated in the ASIC , it is used an external capacitor.

Figure 4.10 shows the schematic of the designed boost converter with external elements. The technology used can afford 50 V. Compared to similar designs made by AMS [20], the diode in the boost converter is usually placed as an external device, leaving free area in the chip which can be used to increase the switch transistor and reduce its resistance. However, as the space available in a capsule endoscope is a hard constrain, a HV-PMOS transistors was integrated in the ASIC and used as a diode in order to reduce area.

The boost converter includes a small circuit to prevent the generation of a voltage greater than 50 V. Such circuit is composed by a resistor divider, a comparator and an AND gate. When the output voltage is greater than 50 V the output of the comparator provides a logic zero to the AND gate, which automatically switches off the transistor M1. If the output voltage is lower than 50 V, the comparator gives a logic one (3.3 V), and the control is performer normally by the FSM.

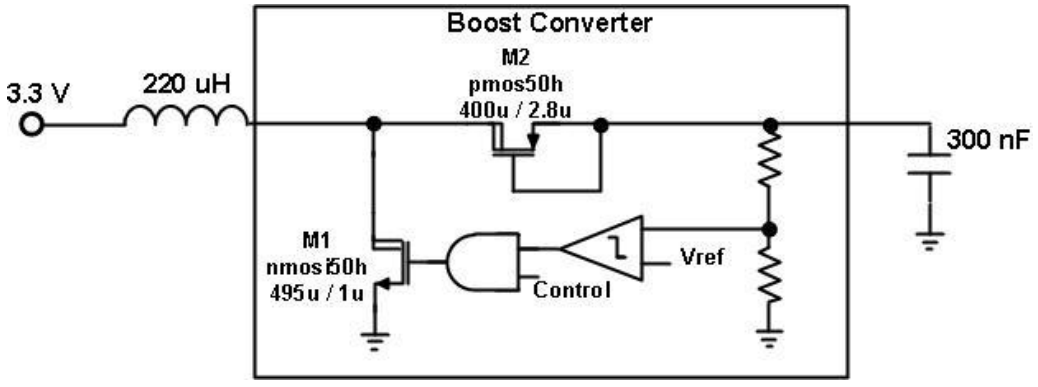

Figure 4.10: Schematic of the DC-DC boost converter. Outside the box are placed the external components.

The M1 and M2 transistors are HV transistors. The M1 transistor is HV-NMOS transistor used as a switch. The size of the HV-NMOS transistor has been selected to limit the current in the switch to 10 mA. The M2 transistor is a HV-PMOS transistor used as a HV-Diode. The size of the HV-Diode has been calculated in order to reduce its parasitic resistance.

4.2.2. HV level-shifter

The HV-PMOS transistors used in the HB cannot afford a $V_{GS} < -20\,V$. So, if the source of the HV-PMOS transistors is supplied at 50 V, the minimum gate voltage must be 30 V. In order to maintain the HV-PMOS transistors of the HB in the safe operating region it is needed to add two HV level-shifters to adapt the controlling signal to the HV-PMOS transistors. It is not required to add HV level-shifter for the HV-NMOS transistors of the HB.

During the operation, the liquid lens driver has to supply voltages from 30 V up to 50 V. It means that the supply voltage of the HB is not fixed, and the HV level-shifters have to be capable to adapt the controlling signals (going from 0 to 3.3 V) depending on the generated supply voltage.

Figure 4.11 shows the schematic of the HV level-shifter used to meet the presented requirements. Basically, transistors M1 – M3 are used to generate a bias voltage (Vdd – 2 |Vthp|), which is used as a virtual ground by the inverter formed by M7 and M8. The current flowing through M1 and M2 is copied to M4 and M5. The current of this branch is also controlled by M6. When Vin is a logic 0, M6 is switched on and the input voltage of the inverter stage is near to the virtual ground, and the output voltage is the supply voltage. When Vin is a logic 1, M6 is switched off, current is not copied and the input voltage of the inverter stage is the supply voltage, being the output voltage the virtual ground. As the output voltage will be applied to HV-PMOS transistors it has sense to invert the signal.

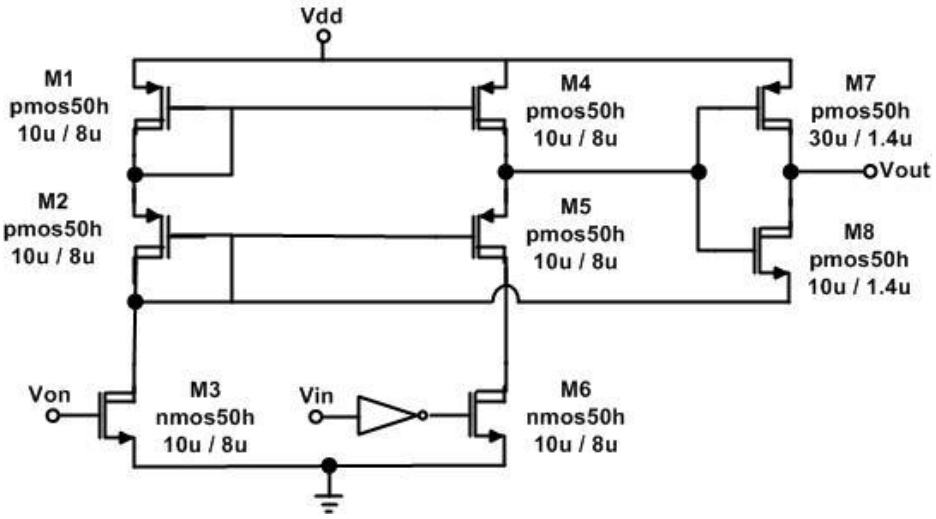

Figure 4.11: Schematic of the HV level shifter.

4.2.3. HV H-Bridge

An HB is an electronic circuit which applies a voltage across a load in either direction. HB circuits are widely used to drive different applications, like driving a DC motor. In this case, a high voltage HB is used to drive the liquid lens. Figure 4.12 shows the schematic of the HV HB circuit. With this simple configuration it is possible to apply a differential voltage to the liquid lens, i.e. 30 to 50 V in one terminal while the other is grounded and vice versa, which is the required operation mode of the liquid lens.

The HB circuit is composed by two HV inverters composed by one HV-PMOS transistor and one HV-NMOS transistor. When the HV-PMOS transistors are switched on, a V_{GS} of -20 V is applied. In contrast, when the HV-NMOS are switched on the V_{GS} is 3.3 V. It is for this cause that the width of the HV-PMOS transistors is almost 8 times smaller than the width of the HV-NMOS transistors for a similar length. The size of the transistors permits to work with a driving frequency of 1 kHz.

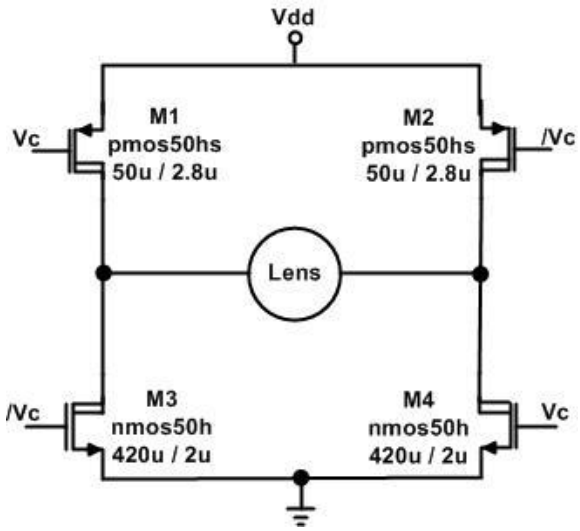

Figure 4.12: Schematic of the HB connected to the liquid lens.

4.3. Implementation and results

The liquid lens driver has been implemented in two different ASICs to prove the functionality of the circuit. In the first one, the driver was implemented without the controller. Figure 4.13 shows the ASIC containing the liquid lens driver. The area occupied by the analog driver is 1925 µm x 500 µm. The second ASIC included the final liquid lens driver and the rest of circuits needed by the control ASIC presented in figure 2.10.

The test of the DC-DC boost converter in the first ASIC shown that the circuit is not able to convert the input voltage up to 50 V with a capacitive charge at the output and 3.3 V applied at the input. Figure 4.14 shows the output voltage of the boost converter versus the duty cycle. The maximum value achieved by the DC-DC converter was 33 V. The main reason for the discrepancy between the simulation and the measurements is that the inductor has a parasitic resistance of 21 Ohms which was not considered in the simulations. Using other inductors, with a lower resistance it is possible to achieve more voltage. Changing the input inductor from 220 uH to 100 uH it was able to reach 42 V.

Although the bad results obtained from the DC-DC boost converter, it was possible to test the rest of the circuit using an external source. Figure 4.15 shows the outputs of the HB when an external voltage of 50 V is applied.

In a second version of the driver the design of the DC-DC boost converter was modified. During the redesign it was taken into account the resistance of the inductor, and it was also reduced the resistance of the switch and the diode in order to improve their behaviour. The driver was included in the control ASIC presented in figure 2.10.

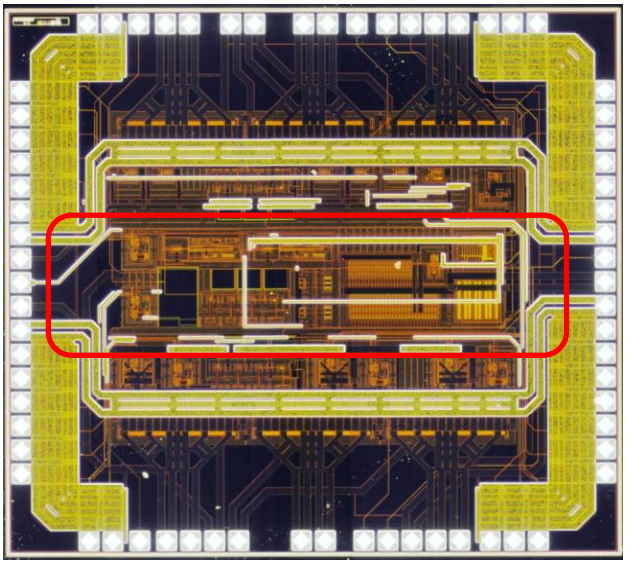

Figure 4.13: Photography of the fabricated ASIC of 3 x 2.7 mm2. The red rectangle highlights the liquid lens driver.

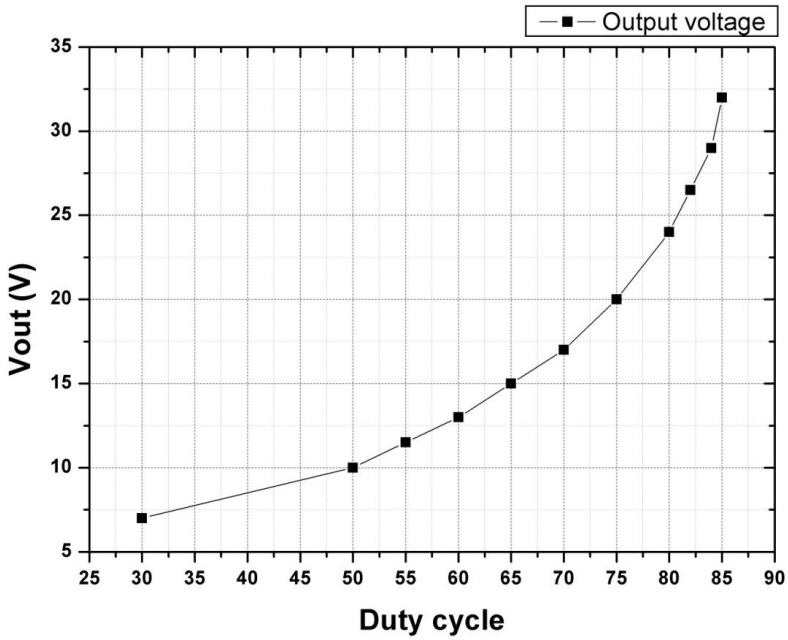

Figure 4.14: Output voltage of the DC-DC boost converter versus the applied duty cycle.

The redesigned DC-DC boost converter presents better results compared to the previous design. With the redesign an output of 50 V is achieved using a capacitive load at the output and 3.3 V at the input. Figure 4.16 shows the output voltage achieved with a Duty cycle of 0.85 and different resistive loads connected at the output. The red points shows the results obtained using an inductor of 100 uH with a parasitic resistance of 10 Ohms. The black points show the results of using and inductor of 220 uH with a parasitic resistance of 21 Ohms.

The modified DC-DC boost converter is able to supply up to 50 V to the liquid lens. Given the simplicity of the DC-DC it has a low efficiency: it needs low resistive loads to generate 50 V and the best efficiency achieved by the boost converter is 72 %. Taking into account that the input power is around 50

- 60 mW there is a big amount of power lost. Nevertheless, it has been proven that the liquid lens driver can be integrated together with the rest of the electronics needed to drive a capsular endoscope robot. Hence, by improving the performance of the DC-DC boost converter the system will be ready to be integrated in future capsular endoscopes.

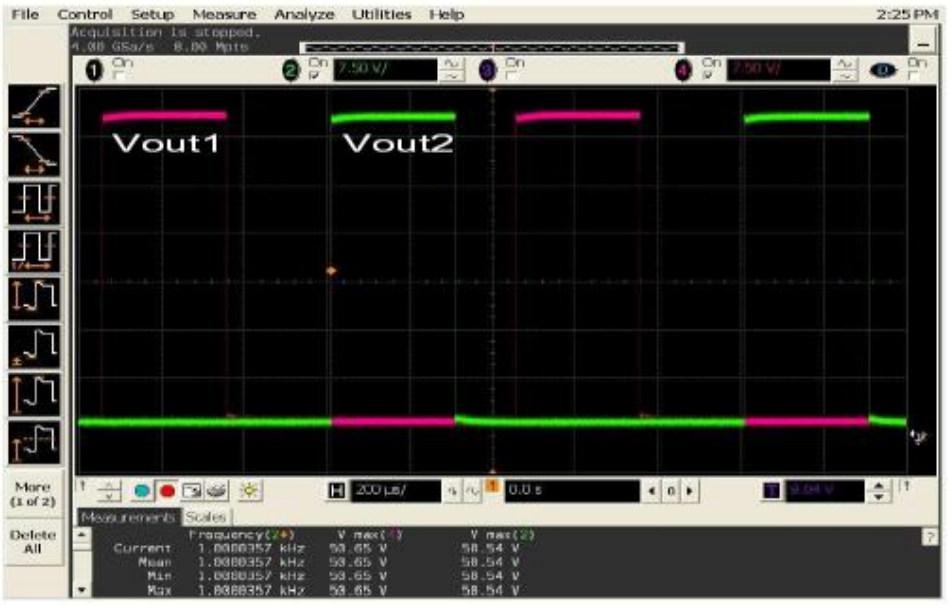

Figure 4.15: Outputs of the HB when an external voltage of 50 V is applied.

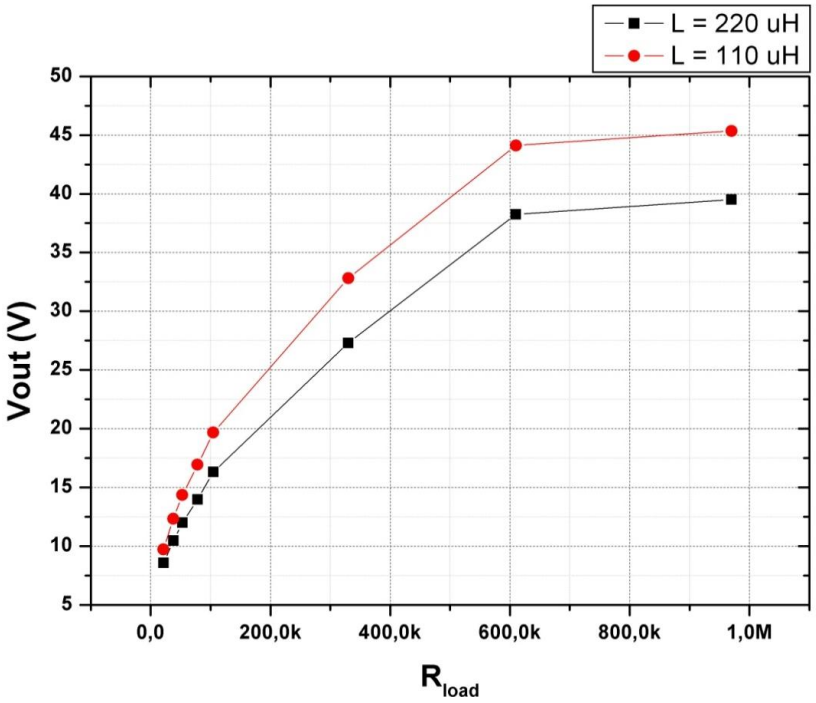

Figure 4.16: Output voltage of the DC-DC boost converter versus the resistive load connected at the output. Results obtained using a duty cycle of 0.8. The red points shows the results obtained using an inductor of 100 uH and a parasitic resistance of 10 Ohms. The black points shows the results of using and inductor of 220 uH and a parasitic resistance of 21 Ohms.

The liquid lens has two electrodes in the external shape. Testing of the liquid lens requires a specific set-up. Figure 4.17 shows the boards used to connect the liquid lens. The liquid lens is placed between both boards like in a sandwich, connecting one electrode to one board, and the other electrode to the second board. Each board must be connected to one of the outputs of the HB.

Figure 4.18 shows the test platform used for testing the complete system. It contains the liquid lens, a camera used to acquire images, the ASIC and the supply sources needed for the ASIC. The liquid lens is in front of the camera. Therefore it is possible to change the focal of the liquid lens and acquire different images with different focal.

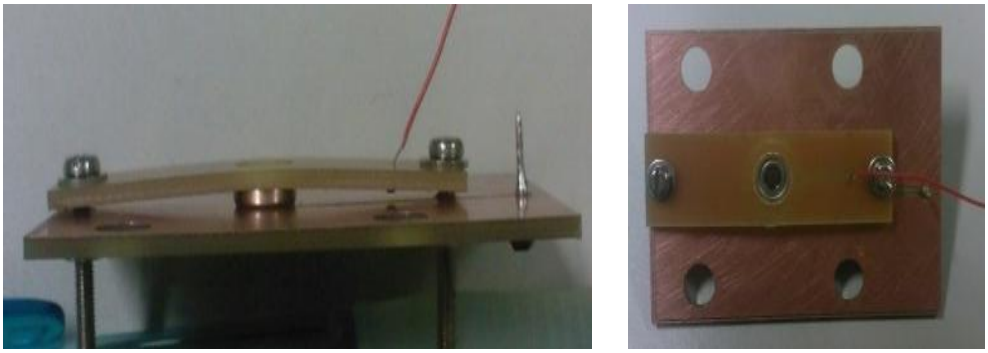

Figure 4.17: Board uses to mount and test the liquid lens

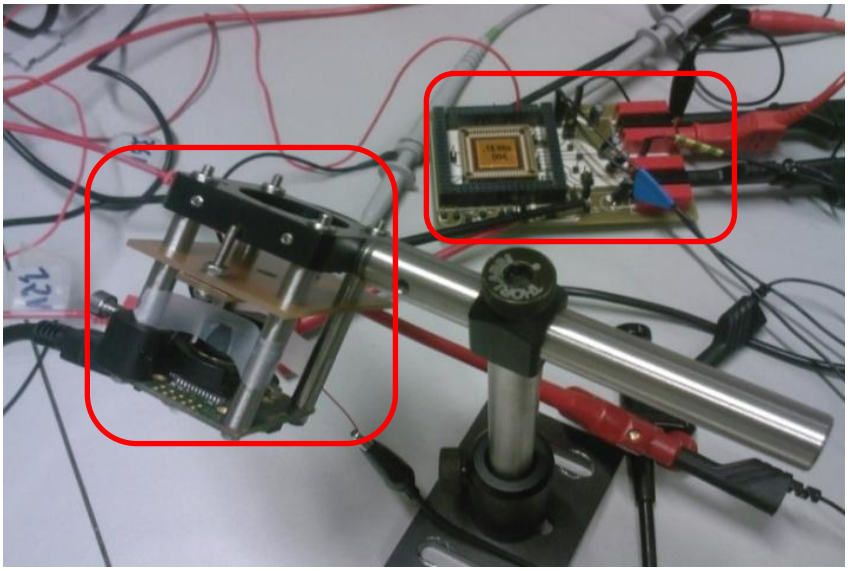

Figure 4.18: Board uses to mount and test the liquid lens. The camera and liquid lens used to acquire images are highlighted as well as the ASIC used to drive the liquid lens.

The test consisted in generating an increasing voltage from 30 V to 50 V with the DC-DC boost converter while driving the HB. Applying the control signals generated by the driver to the liquid lens it can be seen how the focal of the liquid lens changes while the camera is acquiring images. Using this methodology, different images were acquired per different focals (i.e. different supply voltages). Figure 4.19 shows two pictures acquired by the camera using the liquid lens with a supply voltage of 30 V and 48 V. It can be seen that in the first image the liquid lens is not focused while in the second image the liquid lens is focused.

The area occupied by driver integrated into the control ASIC (chapter 2) is compared to other available solutions in the market in Table 4.1. As can be seen, all the presented drivers require external components. The main advance is that the proposed solution can be included in the control ASIC, which reduces dramatically the space used in the capsule endoscope and increases the number of functions to be performed by the control ASIC. It has to be taken into account that the control ASIC must be equipped in all the solution: for the HV895 and Drivic 60 LL3 solutions the control ASIC is needed to drive the capsule, for the MX14515 the control ASIC drives the capsule and it also drives the liquid lens driver because it does not incorporates a controller.

Table 4.1: Area occupied by different liquid lens drivers.

Drivers				
Supertex HV895	**Drivic 60 LL3**	**MAX14515**	**Proposed Driver**	**Control ASIC with proposed driver**
Driver 1x6 mm2	Driver 4x4mm2	Driver 2x1 mm2	Driver 1.9x0.5 mm2	ASIC 5.1x5.2 mm2
Capacitor 1.6x0.8 mm2 (x2)	Inductor 2x1.5 mm2	Capacitor 1.6x0.8 mm2 (x2)	Capacitor 1.6x0.8 mm2	Capacitor 1.6x0.8 mm2 (x2)
	Capacitor 1.6x0.8 mm2 (x6)		Inductor 2x1.5 mm2	Inductor 2x1.5 mm2

4.4. Conclusions

Nowadays capsular endoscopy is moving from passive to active locomotion. Is in this field where the need to acquire better or more detailed images appears in order to guide the capsule endoscope robot or in order to magnify the region under study.

In this chapter, several methods to improve the vision system of a capsular endoscope have been discussed. In particular, it has been chosen to use a liquid lens because it can be easily equipped to a capsule endoscope and because it does not requires too much area inside the endoscope. There are different drivers in the market. The presented driver requires only 1.9 mm x 0.5 mm. Nevertheless, the main advantage of doing a full custom ASIC is that the driver can be integrated together with the rest of the control electronics. Compared with other existing solutions this permits to reduce significantly the total area.

So far, the existing capsules where only completely functional on the small bowel because they are only able to take pictures from a fixed distance. Therefore, if the object is not placed on the focal the picture will not be clear. However, the presented driver enables advanced vision functions like autofocus and zoom function with a power consumption of 88 mW. It improves capsular endoscopy because the capsule is now able to take focused images from every part of the GI tract. Thus, the autofocus function permits to extend the functionality of the capsule to the entire GI tract.

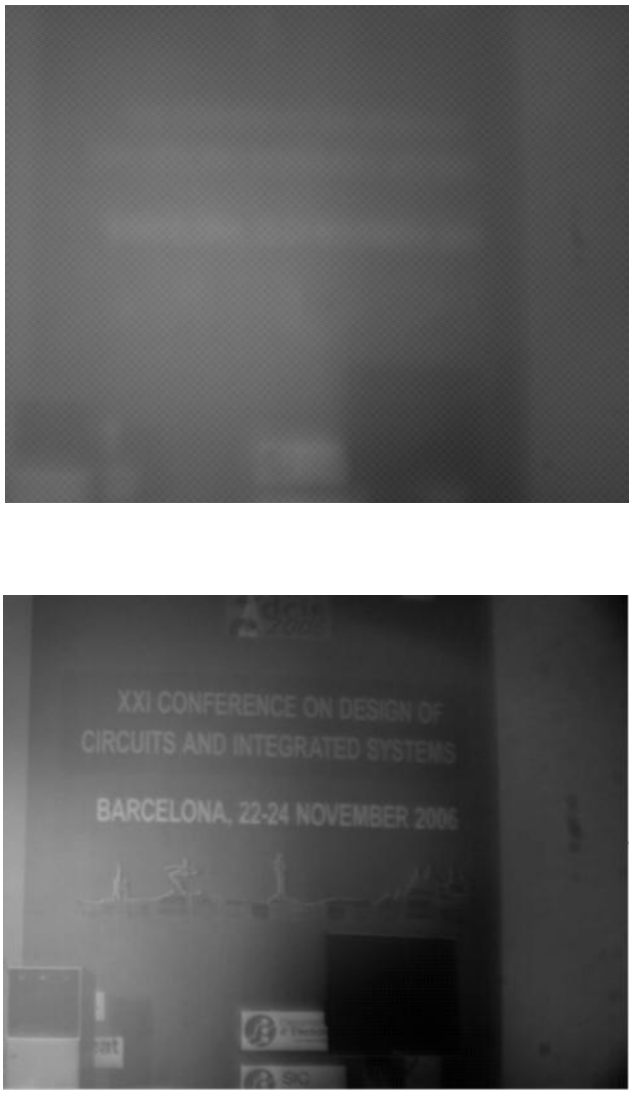

Figure 4.19: Focalizing an image using the ASIC and the liquid lens. The first image uses a generated supply voltage of 30 V and the second image uses 48 V.

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5.Beyond diagnosis in capsule endoscopy by adding therapeutic functions

Traditional endoscopes are able to perform diagnosis and therapy. Common uses of therapeutic endoscopy are stopping GI bleedings, haemostasis, removing polyps, decompression and recanalization of obstructed or dilated bowel, as well as foreign body extraction [1,2]. The main advantage of therapeutic endoscopy is that it can reduce the need of surgery as well as the length of hospital stay [3,4].

Miniaturization of traditional endoscopes has led to the apparition of several capsular endoscope devices [5-7] mainly used for screening and diagnosis. There are few miniaturized robots capable to perform simple surgical tasks like [185] or [186], and few therapeutic capsular endoscopes like the presented in [10]. Such therapeutic device is a capsular endoscope which uses an OTSC clip from Ovesco [11] to enable therapy. Depending on the form of the clip it can be used to stop internal bleedings or it can be used to remove polyps. The movement of the OTSC clip is achieved by means of a BLDC motor. An improved version of this therapeutic capsular endoscope is presented in this chapter.

Compared to traditional therapeutic endoscopes, the therapeutic capsular endoscope has the advantages of reducing the discomfort for the patient and reducing the length of hospital stay. The disadvantages are related to the electronics equipped to the capsule and needed to enable therapy. Firstly, a BLDC motor which generates enough force to move the clip and the electronics to drive it must be fit into the capsule. Secondly, as the therapeutic capsular endoscope is an autonomous device it has to incorporate the supply system, which has to be able to supply enough energy to the BLDC motor. The supply system can be composed by two batteries or by a battery working together with an energy scavenging system as for example the inductive wireless power transfer device presented in [12]. In particular, the driving method of the BLDC motors requires high current peaks during the start-up of the motor, which reduce dramatically the live time of a battery and limit the operation of the inductive power link. If the required current peak is greater than the maximum energy that the inductive power can provide the BLDC will not start. Therefore, there is a need to miniaturize as much as possible the electronics for driving the BLDC motor, and in addition, it is also needed to reduce the current peaks of the motor during the start-up in order to assure the correct operation of the therapeutic capsule endoscope and increase the live time of the batteries.

The aim of this chapter is to use the ASIC presented in chapter 2, which contains the BLDC motor driver presented in chapter 3, to drive a BLDC motor and to enable therapy by means of the OTSC clip. An innovative control method is used in order to avoid the high current peaks during the start-up of the motor. Section 5.1 describes the tool used to enable therapy (OTSC clip). Section 5.2 presents the architecture of the improved therapeutic capsular endoscope and presents in more detail the problems

related to the power supply. In section 5.3 it is presented the low power mode operation of the driver in order to avoid the current peaks during the start-up of a BLDC motor. Based on the low power mode, the test of the driver with an inductive power link and the driver moving the clip are described in section 5.4. The integration of the whole system in a capsule is detailed in section 5.5. Finally the conclusions are presented in section 5.6.

5.1. Therapeutic module

In capsular endoscopy, therapy may be related to simple functions such as tissue sampling and more complex interventions such as removal of polyps (which must have the necessary tools to remove the polyp and stop the bleeding). In particular, this chapter presents a therapeutic capsule endoscope equipped with a surgical clip (OTSC clip), which is basically used for the treatment of GI haemorrhage and for endoscopic digestive organ wall closure. Depending on the form of the clip it can be used to remove polyps.

Internal GI bleedings are a very common disease [13]. Internal GI bleedings may cause acute anaemia and haemorrhagic shock, and may even be life-threatening [14-16]. Using standard techniques, such as traditional endoscopy or fecal occult blood test, is not always possible to detect the GI bleeding source [17-19]. In contrast, using capsule endoscopy or bleeding sensor capsules it is possible to accurately locate the source of bleeding. When this is done, the use of a surgical clip may stop the bleeding.

The OTSC clip for therapeutic capsule endoscopy is a super-elastic Nitinol device for compression and approximation of tissues in the human digestive tract. It can be also used in flexible endoscopy. Figure 5.1 shows a picture of the OTSC clip [11].

Figure 5.1: Picture of the OTSC clip. With permission of OVESCO.

The OTSC clip is delivered by means of an applicator cap mounted to the tip of the capsular endoscope. Based on its unique design the clip closes itself and firmly anchors the tissue to be compressed for hemorrhage or closure of a GI organ wall lesion.

Due to its smart material properties, OTSC clip delivers constant force at the implantation site securing the therapeutic effect. OTSC clip is made of a biocompatible material and can remain in the body as a longterm implant.

The OTSC clip is opened and placed in the capsule endoscope. Therefore, the endoscopic capsule only has to release the clip to close the internal GI bleeding. Figure 5.2 shows how the clip is placed in the capsule endoscope.

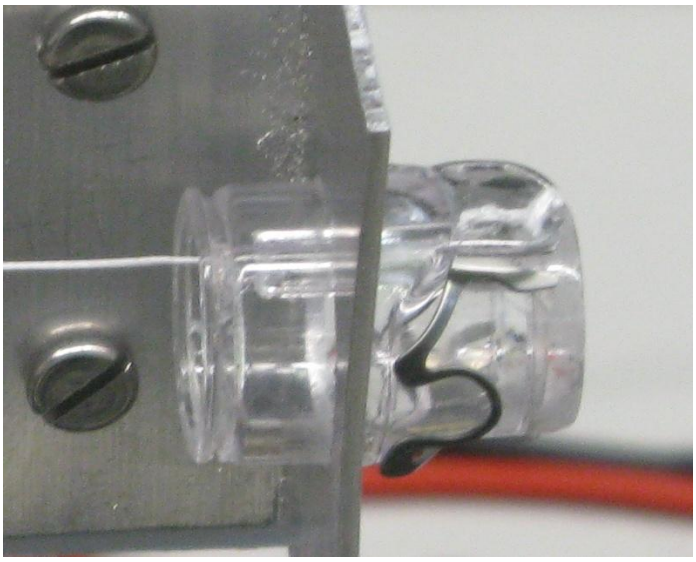

Figure 5.2: Picture of the OTSC clip placed into a capsular shape. With permission of OVESCO.

5.2. Therapeutic capsule architecture

Figure 5.3 shows a schematic of the architecture of the therapeutic capsule. The capsule is 33 mm x 13 mm. It incorporates some magnets for active magnetic locomotion. In the capsule, all the electronic and sensor/actuator modules are off-the-shelf devices, except the ASIC and the inductive power, which have been specially designed.

The endoscope incorporates a microcontroller as the main controller of the system. The microcontroller is connected to a transceiver and to the ASIC described in chapter 2, which is used as a slave device and controlled via serial communication. The transceiver is used to receive external commands. It creates a link between the doctor and the capsule. When the doctor wants to perform a certain operation, an external command has to be sent to the capsule. The transceiver sends the received data to the microcontroller. If the ASIC operation is required by the external command, the microcontroller also sends these data to the ASIC. The main function of the ASIC is to enable the movement of a brushless DC (BLDC) micromotor. The movement of the BLDC micromotor forces the releasing of the clip by pulling a wire connected to the clip edge.

The capsule can be supplied using 2 batteries or using an energy scavenging system consisting in an inductive power link. The main problem of using batteries is that their life time is reduced when the system demands high current peaks, which is the case of a BLDC motor during the start-up [20]. The second power system is more robust to the current peaks because the inductive power supply limits the current to supply. The drawback appears if the BLDC motor demands more current than the maximum

power of the inductive link. In this case the BLDC motor will not start. For the therapeutic capsular endoscope an inductive link capable to supply 400 mW can be used instead of the batteries. More details of this wireless power module can be found in [12,21] and chapter 2.

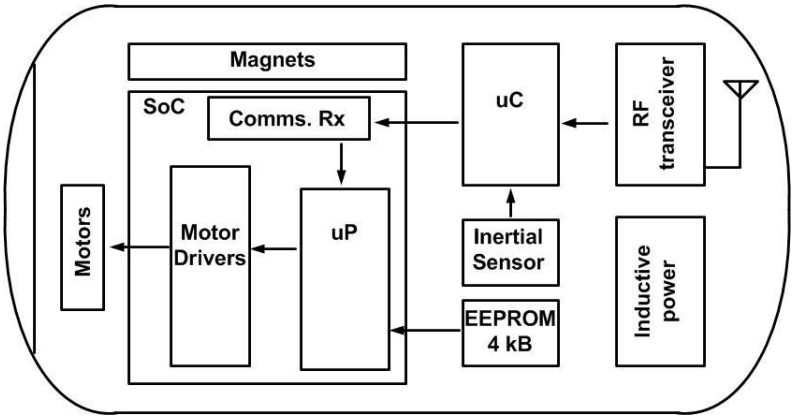

Figure 5.3: Schematic of the architecture of the therapeutic capsular endoscope.

The limitations imposed by both supply systems make necessary the use of some techniques or drivers capable to reduce the current peaks in order to enlarge the battery life or in order to assure the correct operation of the inductive power link.

5.3. Driving of a BLDC motor with a low power start-up

The function of the low power BLDC motor driver is to control and minimize the current supplied to a BLDC motor in order to reduce the current peak during the start-up. Minimizing the supplied current during the start-up means to reduce the starting torque applied to the BLDC micromotor. However, the starting torque has to be high enough to start the movement of the rotor.

The BLDC motor driver has been presented in chapter 3. In this driver, the current supplied to the motor is driven by the 3-phase inverter. The current supplied by one of the NMOS top transistors of each inverter is:

$$I_{Dsat} = \frac{\mu_N C_{ox} W}{2 L} (V_{GS} - V_{THN})^2 \qquad (1)$$

where μ_N is the charge-carrier effective mobility, W is the gate width, L is the gate length and C_{ox} is the gate oxide capacitance per unit area, V_{GS} is the gate voltage minus the source voltage of the transistor and V_{TH} is the threshold voltage. From (1) it can be deduced that the only way to limit the current supplied to the motor is controlling the supply voltage or controlling the gate voltage of the transistors used in the driver.

Limitation of the supply voltage can be performed in practice by using several supplies of different levels. A low voltage supply would be used during the start-up, thus limiting the maximum current delivered to the motor. The number of supply currents is limited by the number of supply voltages and hence there are only few discrete torque values to be used in the torque control. Figure 5.4 shows a simplified schematic of the solution. The driver is composed by N supplies, a 3-phase inverter, a feedback stage to control the motor and the controller.

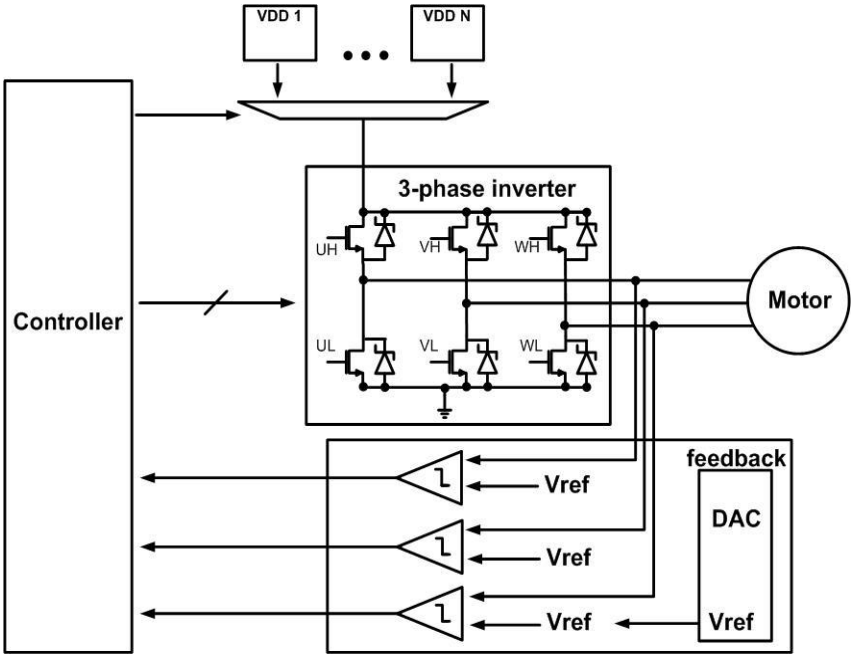

Figure 5.4: Schematic of the driver with multiple supplies.

The control of the VGS of the transistors permits to limit the current provided to the micromotor and control the torque. Figures 5.5 and 5.6 show two different drivers that use this strategy. The main part of both motor drivers 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 be more robust to latch-up. The gates of the NMOS transistors are connected to 6 level-shifters. The level-shifters raise the incoming low voltage signals from the digital control to the voltage generated by the charge pump. The charge pump is based on a Dickson charge pump.

The difference between figures 5.5 and 5.6 is in the way of generating the output voltage of the charge pump. In figure 5.5, the charge pump is supplied with a fixed voltage and controlled by a signal generated by the controller. By changing the frequency of the control signal the output voltage of the charge pump is changed. Therefore, when the charge pump works at lower frequencies, the output voltage is low and then, the VGS voltages are also low. In figure 5.6, the frequency of the charge pump is fixed and the input voltage of the charge pump is controlled by an 8-bit DAC. Using different input voltages in the charge pump the output voltage is also changed. With an 8-bit DAC it is possible to achieve 255 different input voltages for the charge pump.

In our particular case, some elements of the capsule are supplied at 1.8 V. As this external supply is accessible for the electronics, it is more suitable to integrate the circuit presented in figure 5.5 as it requires fewer elements than the circuit of figure 5.6.

The driver has been integrated in an ASIC using the 0.35 um high voltage technology from Austria Microsystems (AMS). The size of the driver is 2 mm x 0.7 mm, and it can be seen in figure 3.16.

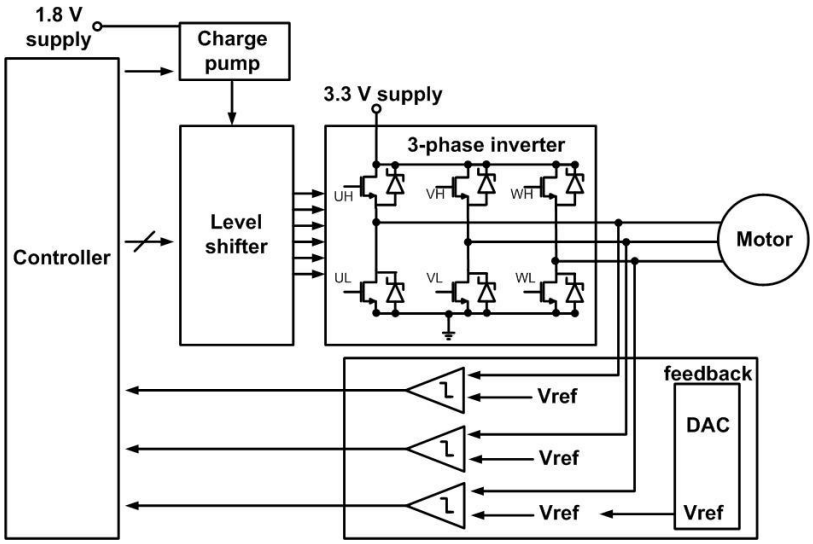

Figure 5.5: Proposed schematic to control the VGS voltage of the 3-phase inverter.

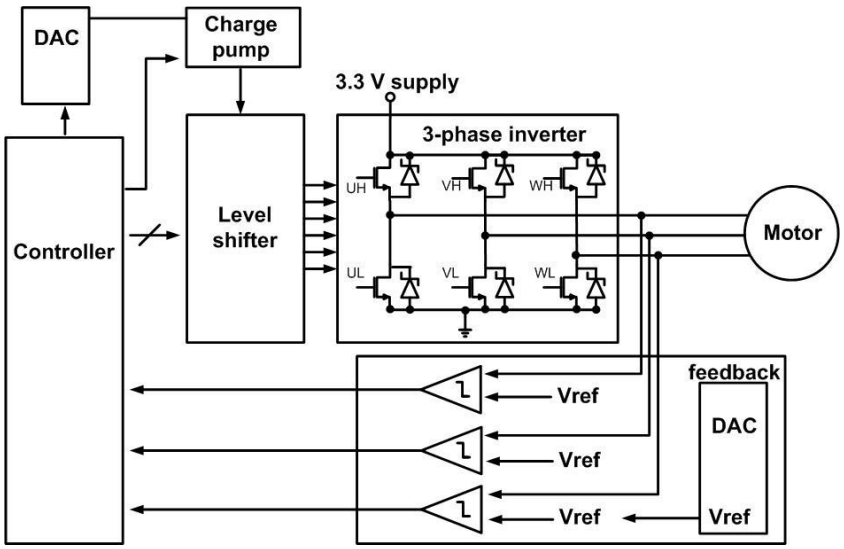

Figure 5.6: Proposed schematic to control the VGS voltage of the 3-phase inverter.

5.4. Results

Three tests have been done to prove the feasibility of the driver in a therapeutic capsule. First, the characterization of the current in a low power start-up and a comparison with a standard start-up is done. Second, it has been tested the start-up and movement of BLDC motor (Namiki) powered by the RF inductive link. A small powering ring is used in this test consecuently a low voltage Namiki motor has been used. The third test is the activation of the clip with the driver. In this case a Flaughabert motor has been used to provide the necessary force.

The low power operation of a BLDC motor driver is a key element in autonomous devices in order to reduce the current peaks. The integrated driver (figure 5.5) is capable of reducing such current peaks during the start-up of the BLDC motor by controlling the charge pump. To demonstrate the low power

operation mode of the driver the charge pump has been programed to generate a ramp from 2.5 V to 5 V in 1 s. The result has been compared to a normal start-up where the charge pump directly generates 5 V. These tests have been done using a BLDC motor from Namiki. Figure 5.7 shows the results of both tests.

As can be seen from figure 5.7, the reduction of the current peak is high. Another advantage of this circuit is that it can be used with current limited power supplies, like an inductive power supply.

The powering system presented in [12,21] is capable to generate up to 400 mW. Nevertheless, for simplicity, the tests are performed with a scaled power system that is capable of generating less power (i.e. 165 mW). Such scaled inductive power system is capable of supplying 50 mA, which are not enough to start the Namiki BLDC motor. Figure 5.8 presents a picture of the test platform. For the test it is needed to use two big coils, which are used to generate a magnetic field. It is also needed the power module, the ASIC and a BLDC motor.

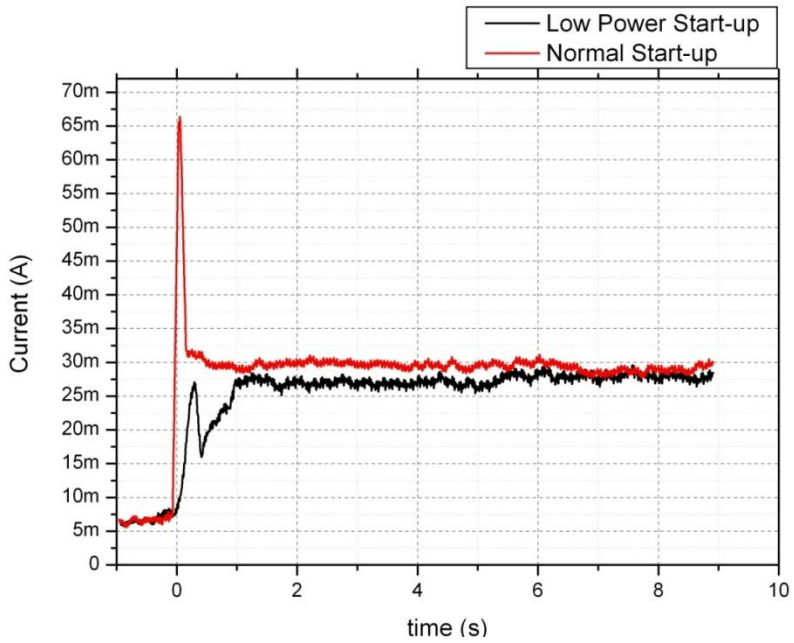

Figure 5.7: Comparison between the current supplied to the Namiki motor in a normal start-up (red line) and a low power start-up (black line).

The big coils are used to generate a magnetic field. When the powering module is inside the magnetic link, the power is transferred to the output of the coils. Such power is used for the ASIC to start the operation of the BLDC motor. The results obtained with this configuration are depicted in Table I. The inductive power module is not able to start-up the motor without stop working. This is due to the high peak of current required by the BLDC at the start-up (in this case more than 65 mA). However, using the low power star-up technique explained in the previous section, the inductive power module is able to power the ASIC and the BLDC motor because the maximum current needed is 30 mA.

For the release of the OTSC clip, a force of approximately 10 N has to be applied to the clip. As the Namiki BLDC motor cannot apply this force, a BLDC motor from Faulhaber is used to release the clip. Such motor is designed to work at 6 V and it is capable of generating a force of 40 N. Nevertheless, as the ASIC works with 3.3 V, the motor will be supplied with 3.3 V. With this supply the Faulhaber motor is still able to realease the clip.

Table 5.1: Results of the Test of the inductive powering

Start-up	Maximum current (mA)	Motor started
Normal	70	No
Low power	30	Yes

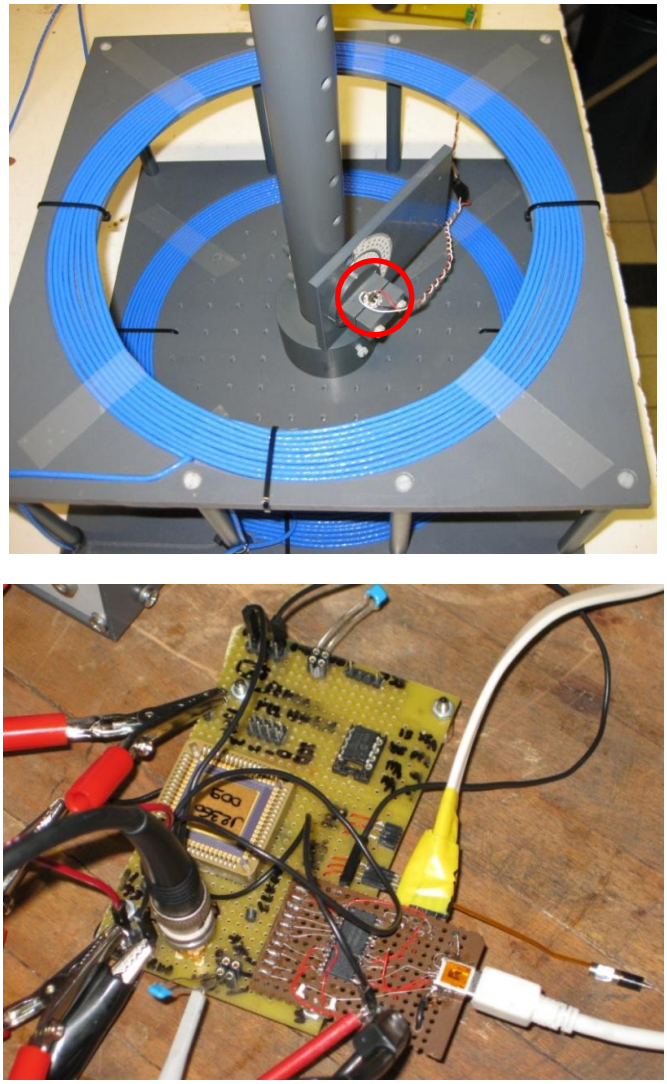

Figure 5.8: a) The picture shows the external coil and the inductive powering placed inside (highlighted). b) The picture shows the test board used to supply the ASIC and drive the BLDC motor.

For the test of the clip, a mock-up of the therapeutic capsule has been used in order to place the OTSC clip. The OTSC clip is connected to the BLDC motor using a thin wire. The motor is connected to the ASIC that will drive it when desired. The system is supplied with an external supply. Figure 5.9 shows an image of the test platform used for this test.

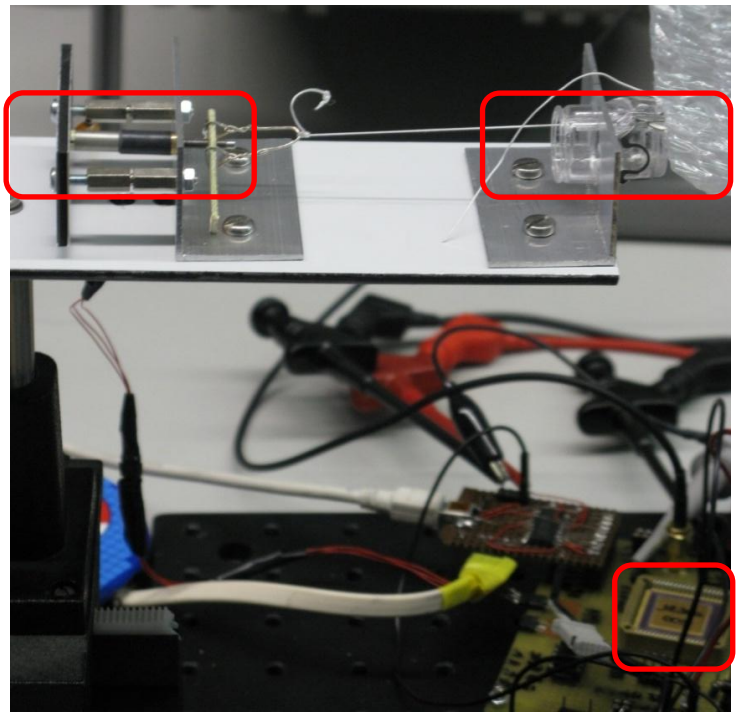

Figure 5.9: Test platform used to prove that the ASIC driving the BLDC motor from Faulhaber is able to release the clip. The BLDC motor, OTSC clip and ASIC are highlighted.

Figure 5.10 shows the power consumption measured during the release of the OTSC clip using the low power start-up.

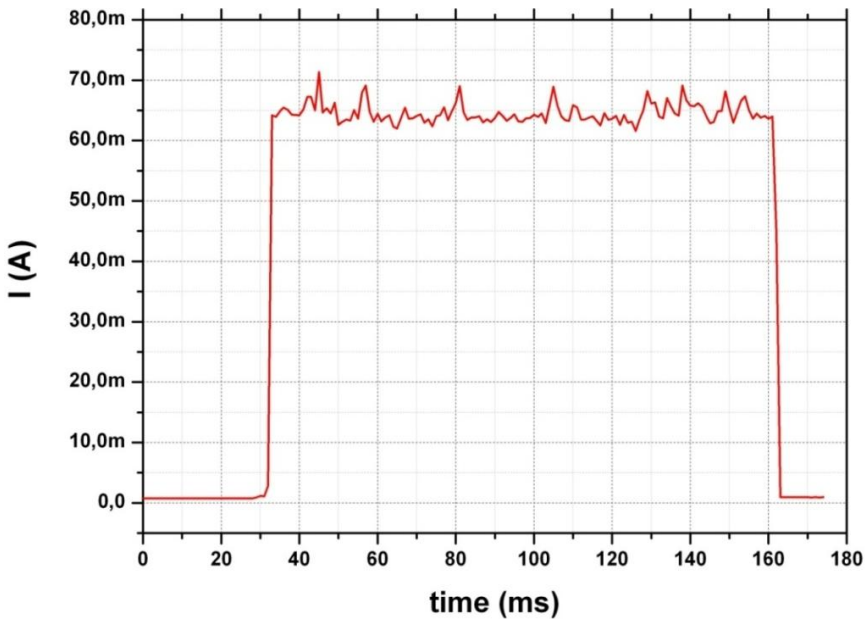

Figure 5.10: Measured power consumption of the ASIC during the clip release operation.

5.5. Integration

The therapeutic capsular endoscope is an autonomous device which presents hard space constraints. Although the miniaturization of each element included in the capsule is a fact, the inclusion of all the electronics in a very small space is a challenge.

The solution in the therapeutic capsule endoscope has been to include the electronic elements in a small flat PCB, where all the electronics except the powering system, the BLDC motor, the OTSC clip and the internal permanent magnets are included. The ASIC can be found in the PCB in the die form. It has been connected to the PCB through wire bonding in order to increase the available space in the capsule. The PCB is 33 mm x 13 mm.Figure 5.11 presents a picture of the top and bottom layers of the PCB with the electronic components soldered. Figure 5.12 shows a detailed picture of the ASIC connected to the PCB without any protecting epoxy.

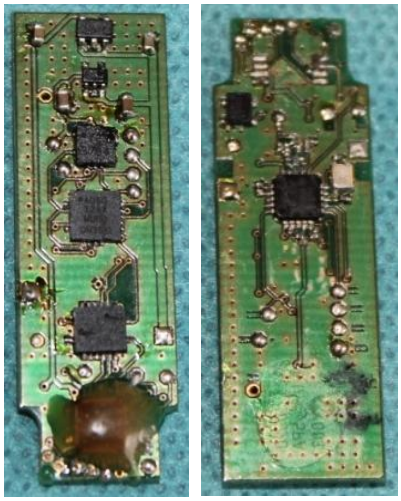

Figure 5.11: Top and bottom layers of the PCB including the electronic components soldered.

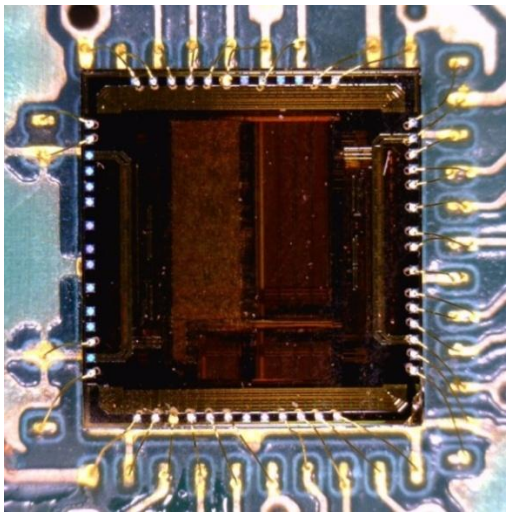

Figure 5.12: Detailed picture of the ASIC wire bonded to the PCB without protecting epoxy.

Finally, a detailed picture of the capsule is presented in figure 5.13. The capsule includes the motor to release the clip (top part), the board including all the electronics (central part) and the magnet used to guide it (bottom part). It also includes the OTSC clip in the front part and the wire needed to release it.

5.6. Conclusions

Since the release of the first capsule endoscope, the research has been focused in improving the capabilities of the state-of-the-art capsules, especially in enabling active locomotion. Nevertheless, in this chapter a step forward has been performed presenting a control ASIC capable of enabling therapy in an active capsule endoscope.

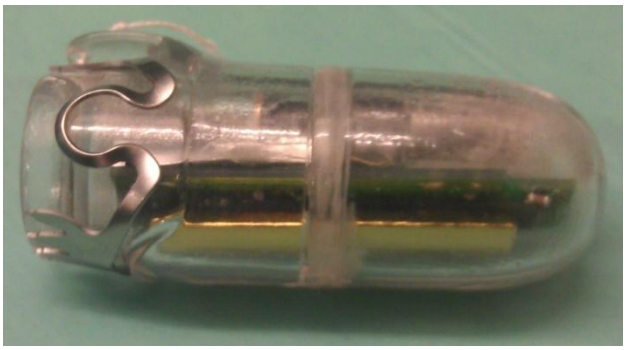

Figure 5.13: Detailed picture of the therapeutic capsule.

The therapeutic capsule uses the OTSC clip from Ovesco to close GI organ wall lesions or internal GI bleedings. Such clip is activated by one BLDC motor which is driven by the control ASIC. The BLDC motor driver included in the ASIC has been specially designed to operate with a low power start-up in order to reduce the current peaks. With this low power mode it is possible to enlarge the life of the batteries or to use an inductive power system which is current limited.

The OTSC clip, the BLDC motor, the control ASIC and the inductive power system plus some magnets needed to enable active locomotion, have been added into a capsular shape of is 33 mm x 13 mm. Due to the size of this capsular endoscope, the region of operation is limited to the colon.

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6.Conclusions

The major medical need in endoscopy is to reduce the pain for the patient. Thus, more people will access to examination, even if they have no symptoms. The mortal incidence due to GI diseases is then expected to be reduced. Capsular endoscopy is a painless alternative endoscopic technique which could be used to substitute traditional endoscopy if some improvements are performed. However, after more than 10 years of the apparition of the first endoscopic capsule, further improvements are still very challenging due to the very high constrains imposed by the available power and space limitations inside the capsule. Better diagnosis and the use of simultaneous diagnosis and therapy are goals for future capsules. For some diseases, an improved diagnosis with capsules can only be achieved by having a complete control of the movement of the endoscope.

This work presents the design and implementation of an ASIC used to enable advanced functions in capsular endoscopy, including active locomotion, better vision and therapy.

A microrobotic capsule endoscope containing as much advanced functions as possible is presented in Chapter 2. One of the ASICs designed in this work is used as a customized solution to control the capsule and enable all functions. Nevertheless, it has been also demonstrated that the total power consumption required for two or more functions at the same time is too high, especially if one is active locomotion. At present time, integrating more than one function is also a problem of space in the capsule. The ASIC has been adapted to provide a unique solution for the control of three simplified capsule concepts: screening, diagnosis and therapy. The ASIC is able also to work in slave mode controlled by an external controller. In this mode it can drive illumination and control micromotors for clipping mechanisms, drug delivery or any other similar function. In the new ASIC size and power have been significantly reduced. At the same time, integrability has been improved.

As a solution to obtain active locomotion in the capsule different motor drivers have been developed. At the same time, these drivers allow drug delivery and therapy with BLDC motors. An important problem with BLDC motors is the unwanted freewheeling currents. This problem has been reduced integrating synchronous rectification which is a standard solution in the industry. To completely eliminate the problem a new driver based on the control of the rise and fall times of the switching control signals has been developed. The new developed method at the same time provides a low power solution.

One of the major advances of this work is that both drivers are able to perform a low power start-up. Due to the architecture used to design both drivers, it is possible to control the energy supplied to the motor. As the most consuming time for a BLDC motor is the start-up region, the drivers are able to perform a low power start-up by supplying less power at this time.

The improvement of the vision in the capsule is done by adding a liquid lens. The main property of a liquid lens is that it can change the focal. Therefore, if a liquid lens is included in a capsular endoscope it will be possible to enable the autofocus function and the zoom function. A specific driver has been designed to habilitate these functions. Nevertheless, in spite of the improvements that can be done to obtain a high performance driving, a liquid lens requires too high power to operate and is unfeasible in a capsule endoscope.

Integration of the ASIC in a real device has been also performed. The ASIC has been used for the control of the release of an OTSC clip in a therapeutic module. The capsule is composed of the OTSC clip, a BLDC motor used to activate the clip, the control ASIC driving the motor, and the electronics needed to supply and activate externally the capsule. The dimensions of this capsule are bigger than the expected (33 mm x 13 mm) because it is needed to add a bigger BLDC motor to activate the OTSC clip. The complete device has been successfully supplied by an external inductive link and operated releasing the clip. This device is a considerable advance in endoscopy as allows to do diagnosis and therapy simultaneously with an endoscopic capsule.

Resumen

La endoscopia en el trato digestivo es la técnica más usada de detección y diagnóstico de enfermedades. Esta consiste en introducir un tubo delgado y flexible por alguno de los orificios naturales del cuerpo (boca, nariz o ano). A pesar de ser el método más fiable de detección y diagnóstico, la endoscopia tiene ciertas desventajas como el ser un procedimiento molesto (en ocasiones se debe sedar al paciente), no puede acceder a todo el trato digestivo, tiene riesgo de infección y el riesgo de perforación.

La necesidad de mejorar este procedimiento ha llevado a la aparición de nuevas técnicas de detección y diagnóstico menos invasivas como el test de sangre en las heces, la colonoscopia virtual o la capsula endoscópica. De todas estas técnicas la que más proyección tiene es la capsula endoscópica ya que en un futuro próximo permitirá obtener los mismos resultados que la endoscopia tradicional.

La primera capsula endoscópica apareció en el mercado el año 2001, introducida por Given Imaging, dicha capsula consiste en una cámara CMOS, una batería y un transmisor colocados en el interior de una cápsula de no más de 10 mm de diámetro por 26 mm de longitud. Comparada con la endoscopia tradicional, la endoscopia mediante capsulas permite explorar el tracto intestinal entero sin causar ninguna molestia para el paciente. Actualmente, todas las capsulas endoscópicas que se encuentran en el mercado son pasivas. Las funciones o elementos básicos de una capsula endoscópica son la visión, la comunicación y la alimentación.

Dadas las ventajas que ofrecen las capsulas endoscópicas frente a la endoscopia tradicional, el principal objetivo es lograr que las capsulas endoscópicas obtenga resultados similares o incluso mejores que los que se obtienen en endoscopia tradicional. Para esto es necesario mejorar las características de la capsula añadiéndole un sistema de locomoción y añadiendo más funciones. La solución propuesta en este trabajo consiste en añadir un nuevo elemento que nos permita obtener una capsula activa, y ser capaces de habilitar y deshabilitar funciones adicionales. Este nuevo elemento es un controlador (CPU).

Debido a las limitaciones de espacio y la necesidad de tener un bajo consumo, es necesario el uso de un ASIC. De esta forma es posible la unificación de la CPU y del circuito que habilita la locomoción en un mismo chip. El ASIC, además, permitirá habilitar otras funciones tal como se muestra en la figura R.1. La figura R.1 ilustra el concepto de la solución propuesta para el caso de la capsula propuesta.

Para habilitar las funciones avanzadas de visión la capsula endoscópica incorpora una lente liquida. Para activar la locomoción se usan micro motores DC sin escobillas. La principal ventaja de usar dichos motores es que también pueden usarse para habilitar otras funciones como biopsia o para aplicar un medicamento en una zona afectada.

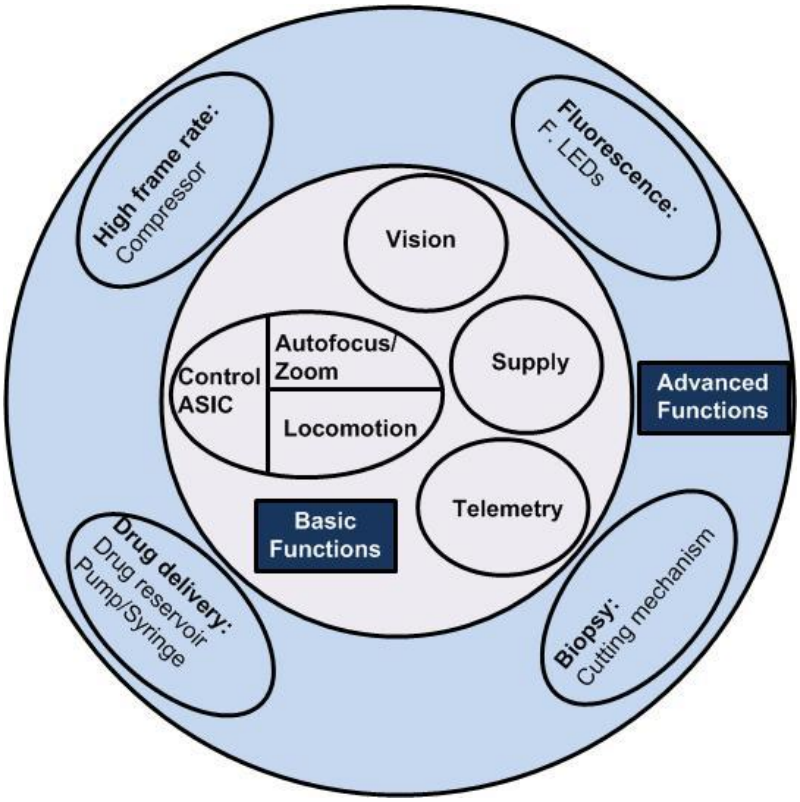

Figura R.1: Esquema básico que ilustra el concepto de la solución propuesta para el caso de la capsula propuesta.

Con esta estrategia es posible abordar distintos conceptos de capsulas activas. En particular, en este trabajo se han presentado dos soluciones distintas para lograr una capsula endoscópica capaz de obtener una mejora frente a las capsulas existentes. La primera solución propuesta consiste en el uso de una cápsula endoscópica microrobotica que contiene tantas funciones avanzadas como sea posible. La segunda solución propuesta tiene en cuenta los principales inconvenientes de la solución microrobotica, y consiste en dividir dicha cápsula en tres diferentes cápsulas especialmente diseñadas para realizar diferentes operaciones en el interior del tracto gastrointestinal. La primera cápsula está diseñada para propósitos de "screening", el segundo está diseñado para el diagnóstico y la tercera está diseñada para llevar a cabo terapia.

La principal diferencia entre ambas propuestas radica en el número de elementos externos que se tienen que añadir en la capsula. En la solución microrobotica es necesario añadir muchos más elementos que en las otras capsulas dado que tiene que ser capaz de habilitar más funciones. Aun así, la estructura básica para todas las capsulas es la misma: los elementos básicos son la visión, comunicación, la alimentación y un CI de control que además permite la locomoción.

Para el caso de la capsula VECTOR, el sistema de visión está formado por una cámara CMOS y 16 LEDs. La cámara toma imágenes, mientras que los LEDs iluminan el tracto gastrointestinal. El control de la iluminación es realizado por el ASIC. La comunicación, bidireccional, es realizada usando un transmisor de campo cercano y modulación FSK de 2 Mbps. La alimentación del sistema es realizada usando baterías y reguladores. Finalmente han sido diseñados dos ASICs de control. En concreto, como la solución microrobotica debe ser capaz de activar más funciones su ASIC contiene más circuitos que la solución de dividir las funciones en 3 capsulas distintas.

Descripción del ASIC implementado en la solución microrobotica:

La Figura R.2 muestra un esquema representativo de la arquitectura propuesta para la solución microrobotica. En este caso el ASIC controla a través de un bus I2C la cámara, el transmisor y un ASIC que actúa de interfaz global de sensores/actuadores. La compresión de imagen debería estar incluida en la cámara CMOS o en el trasmisor, sin embargo ninguno de ellos la incluye. Por esta razón, a fin de que la velocidad de los fotogramas sea alta es necesario agregar un elemento externo que tiene que ser capaz de comprimir las imágenes adquiridas y enviarlo al transmisor. Además, el compresor no puede ser incluido en la interfaz de sensores/actuadores porqué es un elemento fundamental y porqué la interfaz es intercambiable y dependiente de la aplicación.

La arquitectura del ASIC de control usada en esta solución se ilustra en la figura R.3. El bloque principal del ASIC es el microprocesador 8051, que es la unidad de control (DW8051 IP). La inclusión del microprocesador en la cápsula endoscópica es necesaria porque da más flexibilidad al sistema y facilita la depuració. Además, como las funciones a desarrollar no se conocen en detalle, incluir una máquina de estados finitos no es apropiado. Por último, el microprocesador permite añadir funciones robóticas a la cápsula endoscópica a través de software y de los drivers añadidos.

El microprocesador tiene 256 B de memoria interna SRAM, que es el mínimo requerido por el mismo. También dispone de 2 KB de memoria de datos SRAM y 8 KB de memoria de programa SRAM. Este número ha sido seleccionado a partir de experiencias anteriores en otros ASIC. Después de la prueba del ASIC de control será posible determinar con exactitud la cantidad de memoria que realmente se necesita. El tipo de memoria que utiliza es volátil. Por lo tanto, cada vez que la cápsula VECTOR se encienda el programa deberá ser recargado en la memoria del programa. Memorias EEPROM no han sido seleccionadas debido a que no están disponibles por el proveedor de tecnología en el caso de los proyectos MPW y porque no se requieren en esta etapa de diseño. El proceso de programación se lleva a cabo por el gestor de arranque (BL) que interpreta y envía el código binario recibido en el puerto serie a la memoria del programa. Después de que el programa se cargue, el procesador es encendido y realiza la configuración del resto de registros.

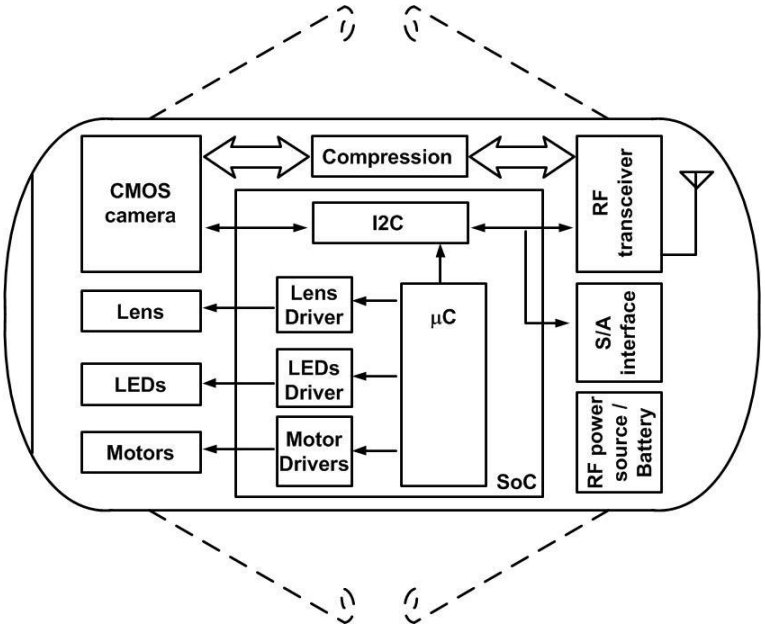

Figura R.2: Esquema representativo de la arquitectura propuesta para la solución microrobotica.

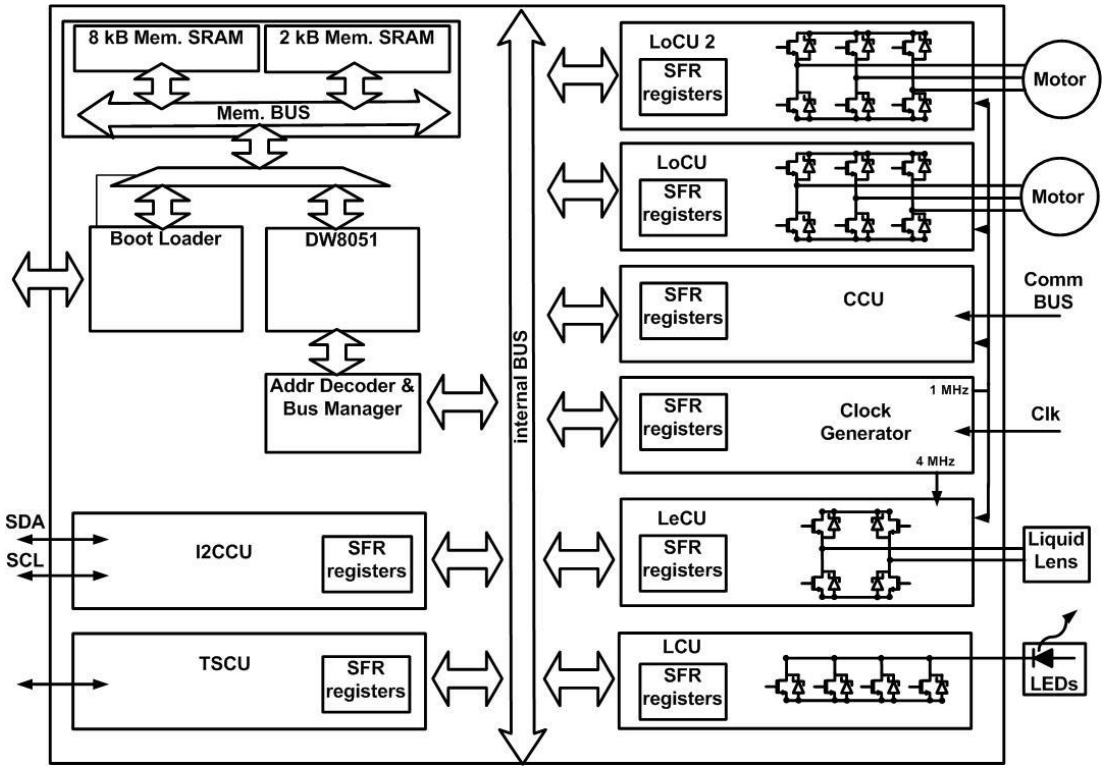

Figura R.3: Arquitectura del ASIC de control usado en la solución microrobotica.

Se han incluido periféricos específicos para cada una de las funciones de la cápsula. Los periféricos, además, determinan el consumo de potencia dinámica de la cápsula. Esta estrategia permite administrar la potencia instantánea para no rebasar la capacidad de la batería. Los periféricos son la unidad de control "time stamp" (TSCU), la unidad de control del bus I2C (I2CCU), la unidad de control de los LEDs (LCU), la unidad de control de la lente (LECU), la unidad generadora de reloj (CGU), la unidad de control de comunicaciones (CCU) y dos unidades de control de la locomoción (LoCU).

Descripción del ASIC implementado en la solución de las 3 capsulas

La idea de usar distintas capsulas con distintas funciones es para poder llegar a explorar a un mayor número de personas. Dado que la endoscopia tradicional es muy molesta, si creamos un dispositivo indoloro que sea capaz de explorar el cuerpo mientras estamos en casa, mucha más gente accederá a realizarse exploraciones. Si en una de estas exploraciones el médico cree que ha detectado algo, puede usar una capsula mucho más compleja para determinar el problema o incluso para solucionarlo.

En nuestro caso nos encontramos con 3 capsulas endoscópicas con distintas funciones cada una. Es por eso, que cada capsula tiene una arquitectura distinta. Las 3 cápsulas pueden incluir el ASIC como el controlador del sistema. No obstante, en esta solución es necesario añadir un compresor de imágenes ya que ni la cámara ni el transmisor lo incluyen. Así pues, en este trabajo se proponen dos soluciones, ambas presentadas en la figura R.4. La primera solución consiste en un rediseño del ASIC de control para incluir el compresor. El principal problema de esta solución es que la tecnología elegida no es la apropiada para esta aplicación (canal ancho y de alto voltaje). La segunda solución consiste en utilizar una "field programable gate array" (FPGA), diseñada en 65 nm. Dicha FPGA puede incluir la función de compresión en la capsula de diagnóstica además de poder ser reconfigurada para realizar otras funciones

en las otras cápsulas. Como la FPGA cumple los requisitos del sistema, dicho elemento es elegido el controlador principal del sistema relegando al ASIC de control a una posición de esclavo en la capsula terapéutica, donde el ASIC se encargará de mover los motores. En este nuevo esquema es necesario modificar ligeramente el ASIC para habilitar la operación de esclavo, mejorar el consumo de energía y reducir el tamaño del circuito.

Las tres cápsulas endoscópicas están especializadas en cada uno de los tres pasos esenciales en el tratamiento del cáncer gastrointestinal (detección, diagnóstico y tratamiento), por lo tanto la arquitectura de cada cápsula es distinta.

En la Figura R.5, podemos observar la arquitectura de la capsula de "screening". La principal función de esta capsula es la de tomar imágenes a baja velocidad y almacenarlas en una memoria para su posterior visionado. Es por esa razón que en la arquitectura tiene en cuenta la adición de un controlador de memoria y de una memoria. Además, la capsula de "screening" también contiene una cámara, LEDs para la iluminación y un ASIC de control para el control de la cámara y de los LEDs.

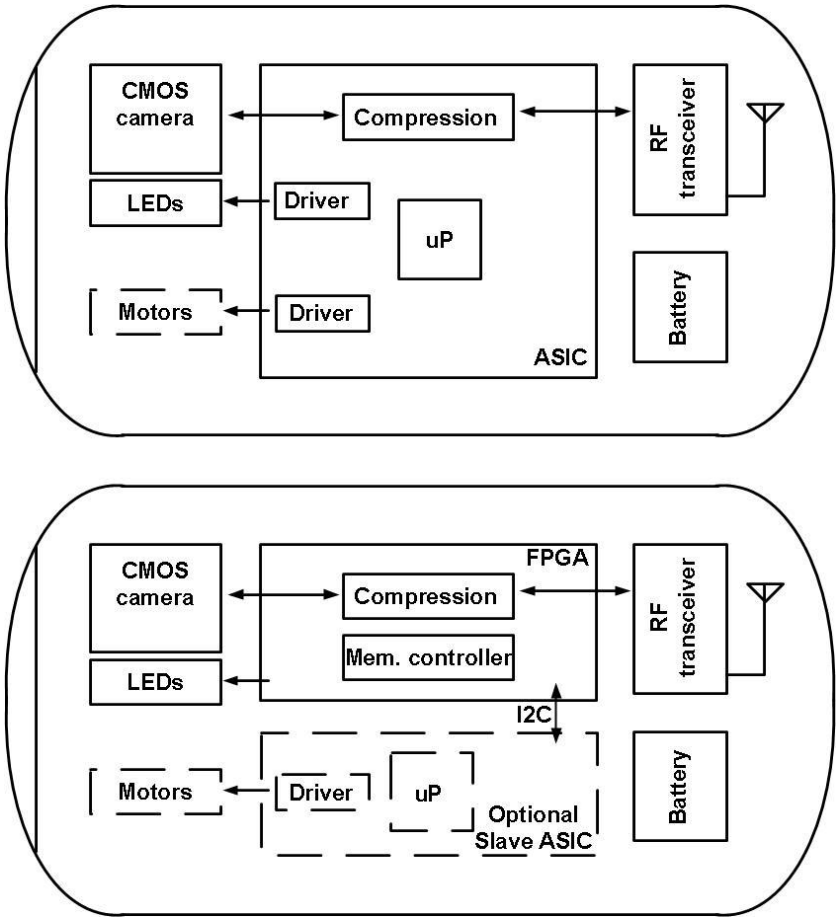

Figura R.4: Arquitectura de las dos soluciones propuestas. La primera requiere el rediseño del ASIC. La segunda incluye una FPGA como controlador del sistema.

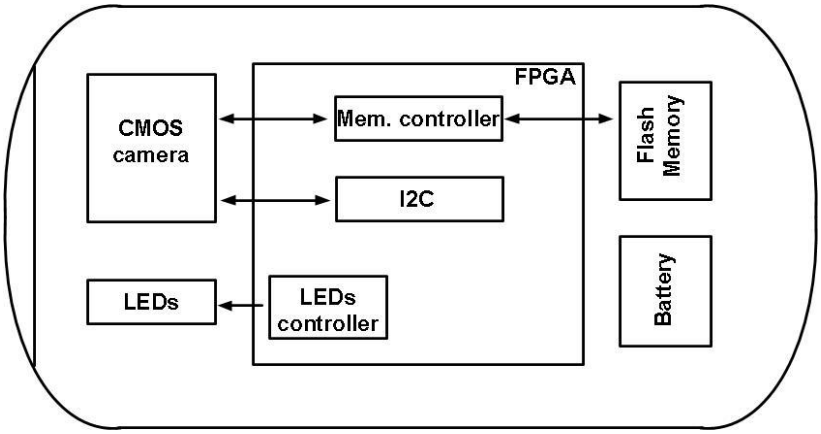

Figura R.5: Arquitectura de la capsula de "screening".

La función de la capsula de diagnosis es un poco distinta, ya que esta debe usar un tipo de LEDs diferentes (para usar distintas técnicas de diagnosis como espectrografía) y además debe poder transmitir imágenes a alta velocidad. Una de las principales características de esta capsula es que contiene unos imanes internos para poder habilitar locomoción activa magnética (la capsula se controla des del exterior con un imán), además, también contiene un sensor de inercia para conocer la posición de la capsula en cada instante. Figura R.6 ilustra la arquitectura de la capsula de diagnosis. Como podemos observar, la capsula de diagnosis sustituye el controlador de memoria y la memoria por un compresor y un transmisor. El resto de los elementos son los mismos que en el anterior caso.

Finalmente, la capsula de terapia es una cáscara, vacía por el interior, que contiene un clip usado para arrancar pólipos o parar sangrados del trato digestivo. La capsula de terapia se sitúa encima de la capsula de diagnosis y sólo es utilizada cuando, en una exploración anterior, se ha detectado un pólipo o sangrado. El clip de la capsula de terapia es activado por los controladores de motor que se encuentran en el ASIC de control.

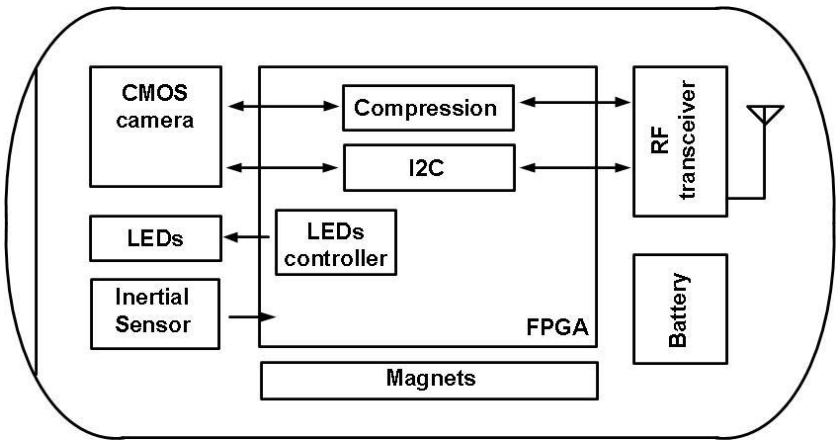

Figura R.6: Arquitectura de la cápsula de diagnóstico.

En la figura R.7 se ilustra la arquitectura del ASIC modificado para ser usado como esclavo en la capsula terapéutica. Tabla R.1 muestra un resumen de las características del chip final. Como podemos observar el ASIC de asemeja bastante al presentado anteriormente, aunque en este se ha usado menos

memoria SRAM (en este caso se usan 4 kB de memoria de programa y 512 B de memoria de datos), se han eliminado algunas unidades de control como la "marca de tiempo" o la lente liquida, se ha añadido una unidad de control encargada de manejar la potencia usada en cada momento, la capacidad de auto programarse cuando se alimenta el ASIC, y, teniendo en cuenta la posibilidad de que la FPGA sea el controlador del sistema, se ha añadido la circuitería necesaria para que el ASIC pueda ser un dispositivo I2C esclavo.

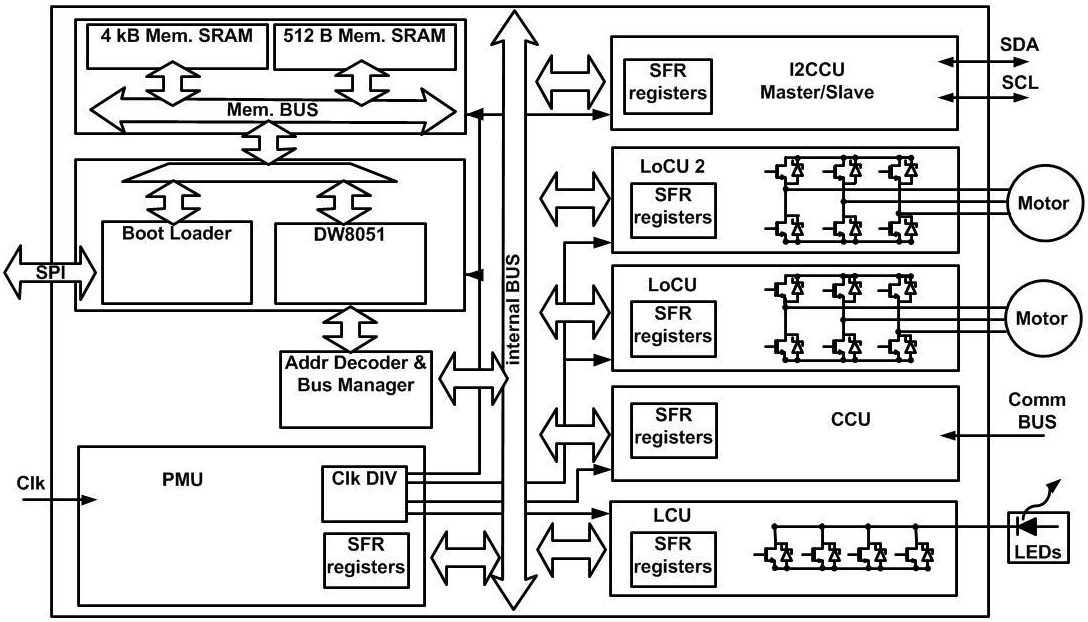

Figura R7: Arquitectura del ASIC de control usado en la solución de la cápsula terapéutica.

Como se ha podido observar, en el diseño de ambos ASIC de control se han añadido algunos controladores con la finalidad de habilitar locomoción activa o funciones de visión avanzadas. Este tipo de controladores son más complejos que el resto y requieren el uso de herramientas de diseño tanto analógicas como digitales.

Como hemos comentado, la principal diferencia entre los dos ASICs de control radica en el tamaño (dado que en el segundo ASIC se han eliminado algunos circuitos y usa menos memoria) y el consumo. El primer ASIC tiene un tamaño de 5.1 mm x 5.2 mm, en cambio el segundo ASIC tiene un tamaño de 3.85 mm x 3.65 mm. La figura R.8 nos presenta una imagen con los dos ASIC fabricados (el segundo ASIC encima del primero). Como se puede observar en la figura R.8, la reducción de tamaño es de aproximadamente un 47 %.

Además, como se ha visto anteriormente, el segundo ASIC añade una unidad de control de consumo. Esto hace que el consumo se reduzca drásticamente en algunas operaciones. La figura R.9 nos presenta una gráfica comparativa de los consumos entre los 2 ASIC, en rojo el primer diseño y en verde el diseño final. Por ejemplo, como se puede observar en la figura R.9, en la operación de "stand by" el consumo se ha reducido un factor 36. Otro ejemplo de la reducción de consumo la encontramos en el arranque de los motores. A través de un sistema de control de corriente añadido en el segundo ASIC es posible controlar la alimentación de los motores, de este modo es posible limitar el consumo durante el arranque de los motores y disminuir drásticamente su consumo. Dicho sistema de disminución de consumo tiene actualmente una petición de patente en curso.

Tabla R.1: Características del ASIC final.

Características	Propiedades	Elementos externos necesarios
Tamaño	3.65 mm x 3.85 mm	
Grosor	250 um	
Núm. de pines	67	
Nº de puertas	20 k	
Memorias	1 SRAM (4 kB) 1 SRAM (512 B) 1 SRAM (256 B)	
Circuitos analógicos	2 DAC (8-bits) 6 Comparadores 2 3-phase inverters 2 Charge pump 1 Power on Reset 6 Level-shifter	
Módulos	LED drivers	16 LEDs
	BLDC driver	36 nF
		BLDC motor
	Master/Slave I2C	2 resistencias de pull up (1 kOhm)
	Unidad de comunicaciones	

Aplicación práctica del ASIC en una capsula endoscópica para terapia

Dados los buenos resultados obtenidos en el segundo ASIC de control (comparados con el primero) se ha decidido implementar dicho ASIC en una capsula prototipo. Dicha capsula se encuentra a medio camino entre la capsula de diagnóstico y la terapéutica. En concreto, la capsula contiene un clip OTSC (necesario para la habilitar las funciones terapéuticas), un motor (necesario para activar el clip), el ASIC de control (necesario para habilitar el motor), un sistema de alimentación inductivo, un sistema transmisor encargado de recibir comandos del exterior (necesario para controlar el ASIC de control desde el exterior), unos imanes para tener locomoción activa magnética y un sensor de inercia para saber la posición de la capsula en cada momento. La figura R.10 muestra un pequeño esquema de cómo es la arquitectura de esta capsula prototipo que usa elementos de la capsula de diagnóstico y la de terapia presentadas anteriormente.

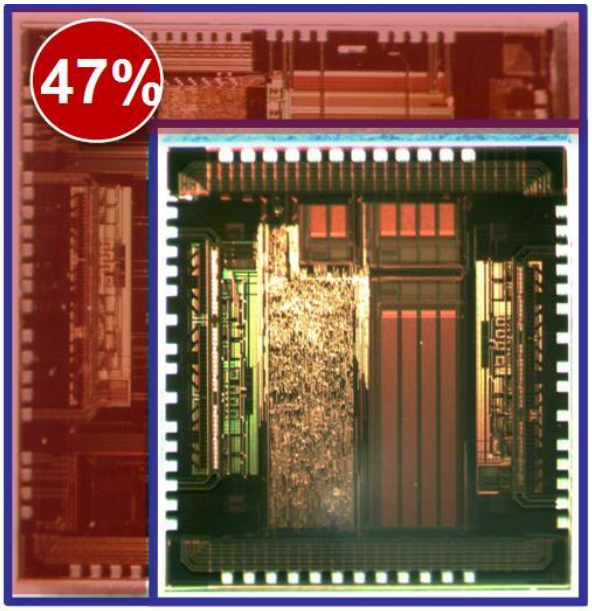

Figura R.8: Fotografía de los dos ASICs usada para comparar sus tamaños. Como se puede ver, la reducción de área es de un 47%.

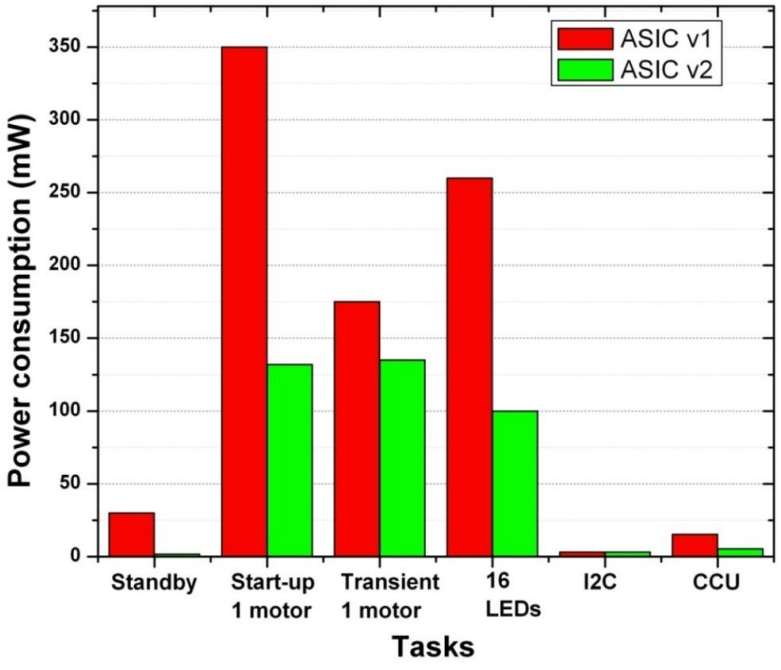

Figura R.9: Comparación del consume de potencia de ambos ASICs de control.

El clip OTSC ha sido diseñado por la empresa alemana OVESCO endoscopy AG. La figura R.11 muestra una imagen de como es el clip en reposo. El clip está fabricado con un material llamado nitinol. Si el clip es colocado abierto en una capsula tal como se muestra en la figura R.12, y a través de algún mecanismo se logra eyectarlo, el clip se cierra automáticamente, haciendo pinza con el material que tenga

delante. Así pues, el clip OTSC es mayormente usado para parar hemorragias internas, o incluso para arrancar algún pólipo.

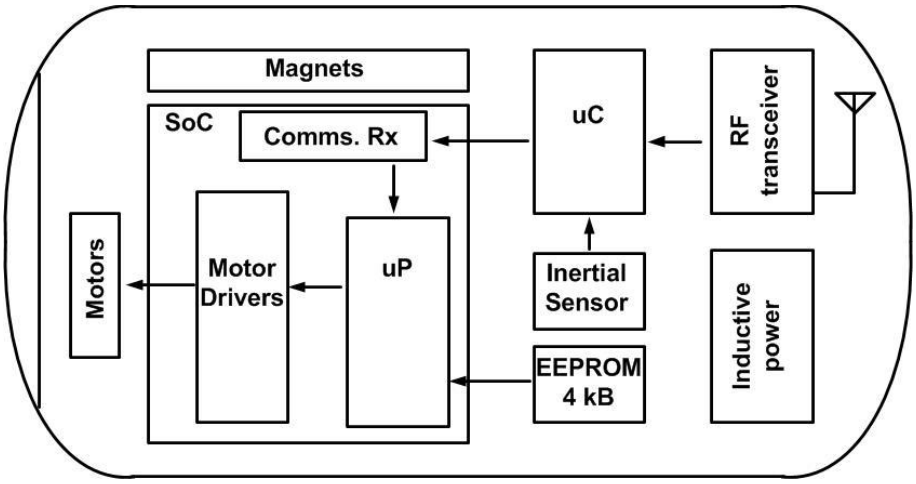

Figura R.10: Arquitectura de la capsula terapéutica implementada.

Figura R.11: Fotografía del OTSC clip. Con el permiso de OVESCO.

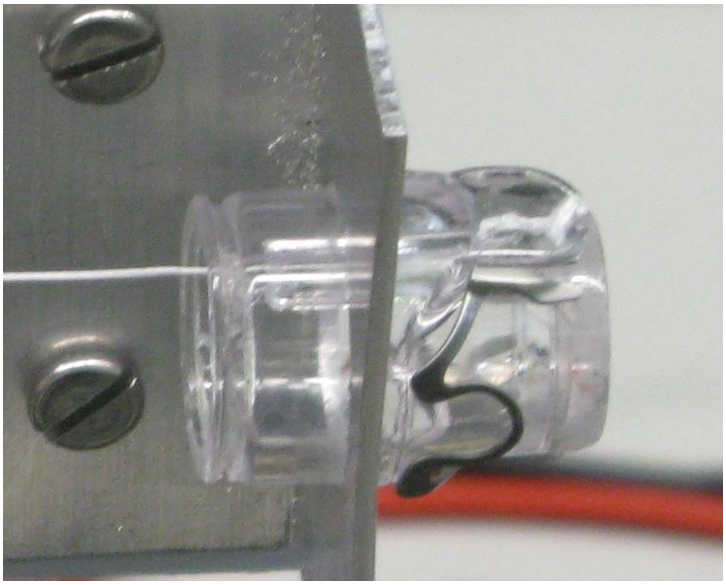

Figura R.12: Fotografía del clip OTSC colocado en un prototipo de cápsula. Con el permiso de OVESCO.

La capsula prototipo tiene un tamaño de 33 mm x 13 mm. En la figura R.13 se puede observar una imagen del prototipo final de la capsula usada para demostrar que el ASIC de control es integrable en una capsula real. En la figura R.14 se muestra una imagen de cómo se ha integrado dicho CI de control en la capsula.

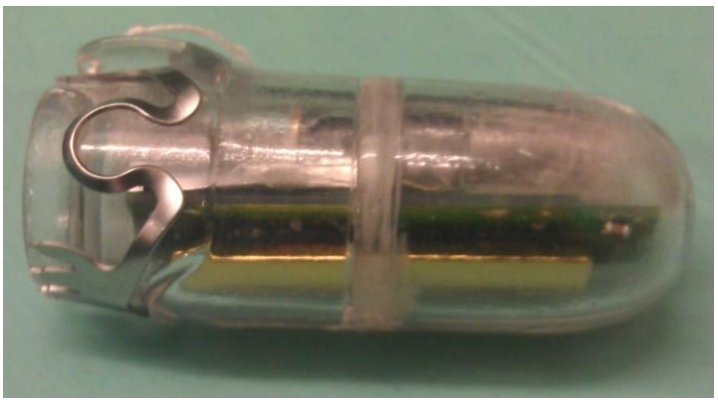

Figura R.13: Fotografía del prototipo de cápsula.

Conclusiones

Este trabajo presenta el diseño e implementación de un ASIC que se utiliza para activar funciones avanzadas una cápsula endoscópica. La principal necesidad médica en endoscopia es poder reducir el dolor para el paciente. De este modo, un mayor número de personas podrían ser exploradas, incluso si no presentan ningún síntoma, y se podría reducir la mortalidad debida a enfermedades gastrointestinales.

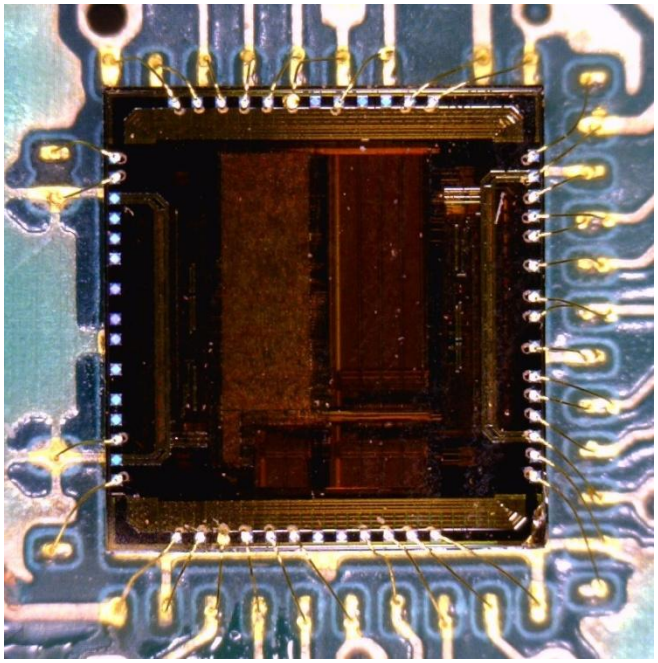

Figura R.14: Fotografía que muestra el detalle de como se ha pegado el ASIC de control a la placa.

Como se ha visto anteriormente, la cápsula endoscópica es una técnica endoscópica indolora y alternativa que podría ser utilizada para sustituir a la endoscopia tradicional si se llevaran a cabo algunas mejoras. Sin embargo, después de más de 10 años de la aparición de la primera cápsula endoscópica, aún es muy difícil mejorar dicho procedimiento debido a las grandes limitaciones impuestas por el espacio disponible en la capsula y por el consumo limitado de esta.

Las principales desventajas de las capsulas endoscópicas son una peor calidad de imagen (comparada con la endoscopia tradicional) y la imposibilidad de controlar sus movimientos (no tiene locomoción). En este trabajo se han propuesto dos posibles soluciones para resolver estos inconvenientes y añadir nuevas funcionalidades a las capsulas endoscópicas. Una de las propuestas consiste en el uso de una cápsula endoscópica microrobotica que contiene tantas funciones avanzadas como sea posible. Como se ha podido observar, que la mejor solución para controlar y activar dichas funciones es con el uso de un ASIC de control especialmente diseñado para esa tarea. Sin embargo, los tests del ASIC de control diseñado para esta solución demostraron que el consumo de energía total necesaria para tener dos o más funciones activas al mismo tiempo es demasiado alto. Además, si también tenemos en cuenta la imposibilidad de miniaturizar y al mismo tiempo añadir tantos sensores / actuadores como sea posible, obtenemos que esta solución es inviable actualmente.

La segunda solución propuesta tiene en cuenta los principales inconvenientes encontrados en la solución microrobotica, y consiste en dividir la cápsula microrobotica en tres diferentes cápsulas especialmente diseñadas para realizar diferentes operaciones en el interior del tracto gastrointestinal. La primera cápsula está diseñada para propósitos de “screening”, la segunda está diseñada para el diagnóstico y la tercera está diseñada para llevar a cabo terapia. Cada capsula endoscópica tiene su propia arquitectura, sin embargo, comparten el mismo sistema de control. Para esta solución particular, un nuevo ASIC ha sido diseñado con el fin de reducir el tamaño y el consumo de energía del primer prototipo. En comparación con la primera propuesta, esta solución es más factible debido a que los problemas de espacio se resuelven mediante la adición de sólo las funciones que sean necesarias en cada cápsula. Además, el consumo de energía se reduce porque hay menos dispositivos electrónicos en cada cápsula, y debido a que se ha añadido un controlador de consumo.

En las dos soluciones propuestas el ASIC de control también contiene controladores LED, controladores de motor DC sin escobillas y un controlador de lente líquida (sólo el primer prototipo) a fin de habilitar tantas funciones como sea posible consumiendo el mínimo espacio y potencia posible. Los controladores LED se utilizan para accionar el sistema de iluminación compuesto por LEDs.

Los controladores de motor se utilizan para habilitar diferentes funciones como la administración de fármacos, locomoción y terapia. El circuito controlador se utiliza para mover un motor que usando unas pequeñas patas, una jeringa o un clip permite la locomoción, la administración de medicamentos o terapia. En esta tesis se ha presentado un circuito controlador del motor que permite arrancar el motor en modo de bajo consumo.

Por último, el circuito controlador de una lente líquida sólo ha sido incluido en el primer ASIC. La principal propiedad de una lente líquida es que puede cambiar la focal. Por lo tanto, si una lente líquida se incluye en una capsula endoscópica será posible activar la función de enfoque automático y la función de zoom. Sin embargo, el principal problema de la lente líquida es que funciona con alta tensión y que consume demasiado para ser integrado en un dispositivo autónomo con otros componentes electrónicos. Por esta razón, la lente líquida fue eliminada en el prototipo de ASIC final.

Finalmente, dados los buenos resultados reportados por el ASIC de control final, dicho ASIC ha sido integrado en un prototipo de cápsula terapéutico. La cápsula contiene, básicamente, un clip de OTSC, necesaria para activar las funciones terapéuticas, un motor, necesaria para activar el clip, el ASIC de control, necesarios para mover el motor, un sensor de inercia y unos imanes para habilitar la locomoción activa magnética, un sistema transmisor para recibir órdenes del exterior y un sistema de alimentación inductivo. Las dimensiones de esta cápsula son grandes (33 x 13 mm), ya que se necesario añadir un motor más grande para activar el clip OTSC.