Abdominal Lighting Simulation System Based On Mini Robots

Sistema de Simulación de la Iluminación Abdominal Basado en Mini Robots

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Abstract

Introduction— This document shows a system that simulates the illumination of the abdominal scene in laparoscopic operations using mini robots. The mini robots would be magnetically tied to the abdominal cavity and manipulated by an external robot arm. Two algorithms are tested in this system: one that moves the mini robot according to the movement of the endoscope, and another that moves from an analysis of the image captured by the scene.

Objective— To contribute to the illumination of the surgical scene by means of mini robots attached magnetically to the abdominal cavity.

Methodology— A software tool was developed using Unity3D, which simulates the interior of the abdomen in laparoscopic operations, adding a new lighting: a mini light-type robot magnetically anchored to the abdominal wall. The mini robot has two different movements to illuminate the scene, one depends on the movement of the endoscope and the other on the image analysis performed.

Results— Tests were performed with a representation of the real environment comparing it with the tests in the built tool, obtaining similar results and showing the potential of a mini robot to provide additional lighting to the surgeon if necessary.

Conclusions— The designed algorithm allows a mini robot that is magnetically anchored in the abdominal wall to move to low-light areas following two options: a geometric relationship or movement as a result of image analysis.

Keywords— Image analysis; Mini lighting robots; Mini robots; Surgical robotics; Unity3D

Resumen

Introducción— Este documento muestra un sistema que simula la iluminación de la escena abdominal en operaciones de laparoscopia utilizando mini robots. Los mini robots estarían atados magnéticamente a la cavidad abdominal y serían manipulados por un brazo robot externo. Dos algoritmos son probados en este sistema: uno que mueve al mini robot de acuerdo al movimiento del endoscopio, y otro que lo mueve a partir de un análisis de la imagen captada por la escena.

Objetivo— Contribuir a la iluminación de la escena quirúrgica por medio de mini robots atados magnéticamente a la cavidad abdominal.

Metodología— Se desarrolló una herramienta software por medio de Unity3D, la cual simula el interior del abdomen en operaciones de laparoscopia, agregándosele una nueva iluminación: un mini robot tipo luz anclado magnéticamente a la pared abdominal. El mini robot tiene dos movimientos diferentes para iluminar la escena, uno depende del movimiento del endoscopio y otro del análisis de imagen realizado.

Resultados— Se realizaron pruebas con una representación del entorno real comparándola con las pruebas en la herramienta construida, obteniéndose resultados similares y mostrando el potencial que tiene un mini robot para proporcionar una iluminación adicional al cirujano en caso de ser necesario.

Conclusiones— El algoritmo diseñado permite que un mini robot que estaría anclado magnéticamente a la pared abdominal, se mueva a zonas de baja iluminación siguiendo dos opciones: una relación geométrica o un movimiento como resultado de un análisis de imagen.

Palabras clave— Análisis de imagen; Mini robots; Mini robots lumínicos; Robótica quirúrgica; Unity3D

I. Introduction

During the last few years, medicine has evolved rapidly to generate benefits for both patients and physicians. Among the most recognized advances is MIS (Minimally Invasive Surgery), a resource that was created to avoid making large and deep incisions in the body of patients. This technique is widely disseminated and its advantages include a reduction in the patient's recovery time, a reduction in the risk of bleeding, and lower hospital costs [1]. The types of surgeries that are performed with this technique are very varied and among these laparoscopy stands out, which has been used in patients of all ages.

Laparoscopic surgery is a procedure in which, through small incisions, the expert introduces an endoscope into the patient's abdomen, obtaining an image of the organs on a monitor [2]. Through these incisions the doctor proceeds by introducing different elements such as forceps, scissors, cauterizers, among others, through the trocars, together with the endoscope or video camera [3].

Laparoscopic surgery stands out for the aforementioned advantages, but it also has several disadvantages such as the delivery of vision in only two dimensions, little sense of depth, and very uncomfortable and stressful positions for the surgeon [1], [4], in addition, due to the long surgery times and the poor maneuverability of the instruments. Faced with these drawbacks, robotics has offered several solutions, among which the Da Vinci surgical robot [1], [5] stands out, which offers greater comfort to the surgeon by providing him with a console where he is seated and from which he can manipulate multiple instruments that filter out tremors and improve their maneuverability. The advantages of the Da Vinci are also reflected in patients who have greater safety in their surgeries and less recovery time.

On the other hand, mini surgical robots have been presented as a proposal to solve the inconveniences shown by large robotic platforms, in addition to generating new advantages for surgeons during procedures such as NOTES (Natural Orifice Transluminal Endoscopic Surgery) or LESS (Laparoendoscopic single site surgery) which would be reflected positively in the patient [6], [7], [8].

The use and demand of surgical robots is increasing and with this the advantages of miniaturizing robotic instruments and assistants are becoming evident [9]. The intention of conducting research around mini surgical assisting robots in general and lighting type mini robots in particular, is to follow the technological trend that foresees that surgical robots will decrease in size so they should be easy to manipulate, to locate inside the human body, and due to this miniaturization, their costs will tend to decrease [10]. Furthermore, this trend will lead to a considerable reduction in the use of large components in robotic assistants [9] and thus laparoscopic surgery may be improved by overcoming some of its limitations [11]. Finally, it should be noted that lighting is a fundamental part of any surgical procedure and procedures performed with robots are no exception.

Mini surgical robots are proposed to serve as assistants during surgeries, especially in the abdominal area. Among the functions that are proposed for these mini robots, the one of being used to fully illuminate said area stands out, being held magnetically through the abdominal wall, this, using robotic arms that will be manipulated externally. Some lighting type mini robots have been used in in vivo experiments as part of cooperative systems to perform natural orifice surgeries. In these experiments, the suitability of using this type of mini robots was shown as they provide adequate lighting [6]. One of the reasons put forward when proposing the addition of lighting through mini robots is to facilitate the surgeon's manipulation to accommodate the lights according to their preferences and avoid unwanted shadows that can reduce visibility or affect the sensation of depth [12]. However, validations performed on a robotic cameraman assistant with an LED lighting system have shown that the surgeon is uncomfortable with the brightness of these lights due to the reflections they produce during the procedure [13]. Although there are proposals for surgical simulators that allow the surgeon to know what their scene will be like before a robot-assisted procedure, they have not studied the incidence of lighting type mini robots in the cavity [12], [13], [14].

Different projects have been developed to miniaturize robotic platforms and provide even more facilities to surgeons. The Miguel Hernández University of Elche, Spain, through the NBIO (Biomedical Neuroengineering) research group, is currently working with a platform made up of two robotic arms that magnetically hold mini robots that assist surgery. This robotic platform was part of the MARCUS project (Micro Abdominal Robot Cooperative System) whose objective is to grant the surgeon new robotic instruments that facilitate their work [14]. In this project, camera, light and forceps type mini robots were designed, working with an augmented reality interface and a complete robotic system to assist single port laparoscopies. The development of this system focused on the operation of the camera and gripper mini robots, while the mini light-type robot was only used to provide the necessary lighting without delving into its operation and the possible advantages or challenges that it can generate both for the surgeon and patient [7], [8], [14]. Likewise, in University of Cauca (Colombia) [15] a first approximation of an environment that shows the patient's abdomen was presented, including a lighting mini robot, built with Ogre 3D.

II. State of the Art

A. *Surgical techniques for abdominal surgery*

1) *MIS*

MIS (Minimally Invasive Surgery) is a resource that was created in the late 1980s [16] as an alternative to conventional surgery and is characterized by allowing the view of the place to be operated without the need to make large and deep incisions in the body of the patients, this thanks to the fact that it uses small cuts through which the instruments are introduced and a camera that transmits the images to a screen through which the surgeon observes the procedure he is performing. This technique is widely used and its advantages and disadvantages have already been mentioned in the introduction.

2) *NOTES*

NOTES (Natural Orifice Transluminal Endoscopic Surgery) is a less invasive procedure than laparoscopy, as it is performed through natural orifices (mouth, vagina, rectum, urethra) and has many applications such as transgastric and transvesical peritoneoscopy, transvaginal tubal ligation, hysterectomy and cholecystectomy [3]. Human procedures using this technique started between 2006 and 2007, although animal experiments started from 2002 [17]. To perform this procedure, other types of instruments such as flexible endoscopes that were commonly used to perform simpler procedures than surgery must be used.

Among the advantages of this type of surgery are the absence of scars, pain reduction, fewer complications, outpatient nature, reduced risk of infection and hernia formation, and shorter recovery time [18]. However, it also has several disadvantages such as the need to use expensive instruments, risk of perforating other organs along the way, bleeding [7], infections, and limited visibility [18]. To solve the drawbacks of this procedure, robotics has shown to have the potential to innovate in this technique through the design of modular miniature robots that can improve the surgeon's experience by collaborating with vision, stability and manipulation [19]. Platforms such as MASTER (master and slave transluminal endoscopic robot) have been designed to expand sensory feedback and increase user dexterity by increasing NOTES capabilities [9]. On the other hand, the ViaCath system is designed exclusively for this procedure. It is a teleoperated endoscopic robot with a haptic interface and interchangeable instruments that provide precision during the procedure and increase maneuverability [9], [20], [21].

3) *LESS*

The LESS (Laparoendoscopic Single Sit) is an intermediate procedure between MIS and NOTES, which is performed as its name indicates, through a single abdominal incision of approximately 1.5 cm, generally umbilical, through which the camera enters and surgical instruments. For this, through the umbilical incision several trocars or special trocars with several entrances can be placed, which are in continuous development and have become one of the research points in the development of surgical instruments. LESS is used to perform different procedures such as appendectomy, cholecystectomy, radical prostatectomy, hysterectomy and radical cystectomy, among others [22]. In addition to the advantages that traditional laparoscopy already has, this technique presents less damage as it has fewer incisions, less pain, less risk of infection, quick recovery and a better aesthetic appearance, however, it introduces new challenges since it reduces triangulation, transposition and collision of surgical instruments and online view of these, which diminishes the surgeon's skill by complicating a procedure that can be very simple with another technique [6].

B. *Surgical robotics*

Robotics has evolved to make life easier and better for people. From industrial robots to home assistants, they are part of the electronic objects that are common in companies and homes. For almost 30 years, robotics began the process of entering the field of medicine by offering solutions and improvements to two important branches of this science: rehabilitation and surgery. Thus, medical robotics is mainly composed of three areas of application: surgical robotics, rehabilitation robotics and assistance robotics [23].

Surgical robotics was born to solve problems presented during and after surgeries such as risk of bleeding, late recovery or discomfort of the surgeon. The idea is to have a robot within the operating room that improves the surgeon's skills without replacing her and that is a tool that can be used comfortably and increases the advantages of the different surgical techniques.

Surgical robots have been designed for various types of surgeries in the areas of neurology, orthopedics, cardiology and abdominal surgery. The latter has been the area of surgery that has benefited the most from the continuous development of surgical robots.

C. *Miniature robotics applied to medicine*

The field of study of miniature robotics is mini or micro robotics. As its name implies, the study focuses on robots of size and dimensions on the order of centimeters or millimeters. The name micro robot has been extended to all small size robots, but according to a specific size one can also speak of mini robots. Miniature robots began to be studied relatively recently thanks to the appearance of the microcontroller that allowed the miniaturization of different electronic equipment. This allowed miniature robotics to develop rapidly in recent years by lowering manufacturing costs. Miniature robots can be of various types: terrestrial, swimming, flying and swarm (which can be made up of any of the indicated types) [24], [25].

In medicine, although the great surgical robotic assistants such as the Da Vinci have represented multiple advances in laparoscopic surgery, they still show drawbacks related to their large size, their handling, the difficult access to some parts of the human body and their high cost. Looking at the evolution of technology into the future, there are many development vectors that will replace or complement assistive robots. These include the use of mini robots to solve problems of access to complex places in surgeries, improve cancer treatments and biopsies, and reduce patient discomfort, pain and recovery time [26]. Miniature robots can be used to assist in surgery or to diagnose and some can correct visibility and accessibility problems.

In various research centers around the world, various mini biomimetic robots focused on medical assistance and treatments have been developed, taking as reference worms, bacteria, sperm or leeches [27], [28], [29]. Robots in the form of pills have also been considered and developed, whose main drawback is the lack of control over their movements [30].

Current efforts are focused on designing mini robots capable of operating in a hostile environment such as the human body, since one of the greatest obstacles in this area is locomotion within a living organism [31]. Also, another drawback is the lack of control of the movements of a mini robot. The most innovative and recent solution is tclahe use of magnetic fields (external magnet that guides the internal mini robot) to have greater control over them, further reduce their size and avoid extra expenses in actuators or other elements [24].

In this regard, multiple types of mini magnetic robots have been developed and proposed, which claim to be a solution to problems such as lack of space in the abdominal area when performing surgical procedures [32], and the generalization of abdominal surgeries by a single entrance or through natural orifices. Depending on the type of procedure they attend, these mini magnetic robots can be camera type [33], [34], forceps [35], light source [34] or devices to perform biopsies [30]. Their designs have been based on magnetic anchoring technology [36], which has allowed the design of instruments that can be manipulated with magnets external to the body without causing damage to the patient's tissues [37], and its use has also generated several advantages over conventional procedures such as laparoscopy [38].

One of the most widely used magnetic anchoring technologies in surgical procedures such as LESS and NOTES is the MAGS magnetic anchoring and guidance system [32]. This system can support various instruments, such as cameras, lights, forceps, cauterizers, small tools to move organs without damaging them [39], and also deployable instruments which have served as the basis for the design of mini robots [40]. It also improves triangulation, visibility, ergonomics, and surgeons' perceived workload [41], [42]. Among its disadvantages is the slow learning curve that it has as it is a recent technology and still requires many experiments to improve the practice and experience of the doctor.

Another application of miniature robots in medicine that is being investigated is the area of surgical assistance. For a mini robot to be suitable for assisting a surgeon during a procedure it must be small enough to enter the human body, but also of a size such that it can be observed and manipulated by surgeons. This is how folding robots are proposed, which can enter the body through a very small incision or natural hole and once inside they unfold to their original size, where they can be used as a camera, light or even forceps, and will generate more safety to the surgeon and therefore to the patient. One of these mini assistant robots was developed by the University of Nebraska, United States, and tested in vivo. It consisted of a platform with a folding tripod that contained a camera and led lights, it could also rotate 360 degrees and tilt 45 degrees. Its design is intended to assist laparoscopic surgeries and the surgeon can activate it from the outside by means of a switch [40]. This same research group improved the mini folding robot by adding wheels, and later creating new wireless versions [26]. This work from the University of Nebraska evolved into the creation of the Virtual Incision company that finished developing a miniature robot for in vivo procedures (Miniature in Vivo Robot-MIVR) known as MIRA and which is awaiting FDA approval to initiate procedures in humans [9], [43].

D. *Lighting challenges during the application of mini robots in minimally invasive surgeries*

When using mini robots as assistants to illuminate laparoscopic surgeries, the effects of light on the scene must be taken into account, how reflection works, how it affects the type of lighting and how shadows change.

The illumination during a conventional laparoscopic surgery is given by an optical fiber that is generally located in the center of the endoscope, its diameter is approximately 11 mm and the distance between the light source and the endoscope objective can vary between 40 mm and 100 mm. It is also possible to introduce several light sources that can improve surgical orientation or have different illumination channels, as is the case with the robot DaVinci's endoscope [44]. These characteristics, as mentioned previously, can affect the surgeon's peripheral vision or the apparent speed of movement of the instruments in addition to reducing the sensation of depth, among others [45]. Within the abdominal cavity, illumination can be affected by various reasons such as shadows and specular reflections, obstruction of visibility by smoke or blood, or by background textures [46].

A drawback that must be constantly anticipated is reflection (diffuse or specular) in the images obtained during laparoscopy. Specular reflection seen in surgical instruments and wet tissues is more common in surgery. The specular reflection can be stronger when the light falls frontally on the surface to be treated, which can cause discomfort to surgeons during diagnosis or surgical procedures, in addition to affecting potential technological applications such as augmented reality [47], [48].

However, although it may be inconvenient, the specular reflection should not be totally eliminated as it is useful when it comes to seeing the geometry of the image during operations, that is, it is useful for the surgeon [49].

In the same way that specular reflection can help the surgeon during a laparoscopy, so can shadows that used properly can improve the surgeon's performance by giving a better idea of depth or by enhancing the image [22].

The above is mentioned for conventional laparoscopic surgeries; however, much technological research is being carried out to improve image quality within the abdominal cavity, improve depth perception and even surgeon feedback during laparoscopic surgery procedures both conventional and robotic. Given this, the presence of shadows or excessive specular reflection are some of the inconveniences to be solved.

There are several algorithms and methods that can solve the presence of undesirable reflections, but they consume a lot of computational resources. Other types of proposals are oriented towards varying the type of lighting in the scene, and although they seem to be efficient, their application in surgeries is not feasible as it directly affects the quality of the image seen by the surgeon [49].

Given this, engineering is studying ways to optimize image quality and help improve surgeon performance with proposals such as changing the type of lighting or a different positioning of one or more lights within the abdominal cavity. Among these proposals stands out that of changing conventional fiber optics for lighting made with LEDs, which generates many advantages such as sharper shadows, better lighting, greater image intensity or less flickering [50].

For almost a decade, the use of miniature platforms that place various types of instruments such as cameras, lights or forceps on the abdominal wall has been proposed [51]. This solution proposes introducing the instruments through a conventional 12 mm trocar and locating them in the abdominal wall using a suture, the light can be adjusted from the control panel and the camera can be manipulated via a joystick. The use of these platforms has been shown to have advantages over conventional laparoscopic or single port surgery, especially in terms of procedure time and scope of instruments.

Lights are always tied to cameras, which is why most of the cited literature talks about improving, designing or magnetically anchoring cameras. Many of the redesigns of these cameras include LED-type lights that are usually very similar to conventional lights used in laparoscopic surgery [52] Using this type of lighting seems to be sufficient and it is emphasized that what the authors seek is to improve not only quality of the image but to replace the conventional endoscope to avoid conflicts of this with the other surgical instruments. It is stated that the lighting within a surgical environment must be efficient and uniform to guarantee the sharpness of the image and that it must exceed the minimum light intensity for the cameras to be in adequate working conditions [53].

By proposing a new location for the camera and lights in a MIS or LESS surgery, the researchers not only want to promote a new type of vision and illumination but also to solve other problems such as the effect on the sharpness of the image when the lenses of the endoscopes become "dirty" in part due to the difference in temperature between the operating room and the interior of the patient, something very common in conventional laparoscopic surgeries. These same authors show that the quality of the image can be improved by using a configuration of LED lights magnetically attached to the abdominal cavity, which reduces shadows within it. In addition, this design does not have the lights fixed to the side of the camera which allows them to focus on a certain area and provide higher quality illumination [54].

III. Methodology

A. *Tool overview*

The proposed tool seeks to implement the movement of a lighting type mini robot magnetically attached to the abdominal area, which is a component of the system of the Miguel Hernández University (UMH)'s laboratory in Elche, Spain (Fig. 1).

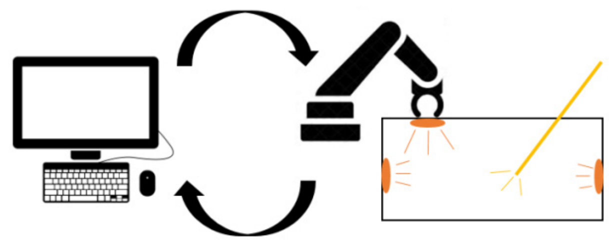

Fig. 1. Scheme of the UMH laboratory's component.
Source: Authors.

For the development of this tool, the Blender programs were used for the design of the organs, Unity3D for the design of the graphic tool and its operation, the OpenCV computer vision library for the image analysis and the C # and Python languages.

In conventional laparoscopic surgery, the abdominal cavity is insufflated with CO2 to form a hemisphere (Fig. 2), on the other hand, in the UMH laboratory characterization the abdominal cavity is represented by an acrylic box (Fig. 3). Therefore, an approximation of the abdominal cavity was considered for the software tool, taking into account the two scenarios for the implementation of the robot movement (Fig. 4). The elements for the simulation, including the mini robot, are introduced into the representation of the abdominal cavity through the trocar, as is done in conventional laparoscopic surgeries, and are clamped using MAGS technology. The mini robot, as its name implies, must be small in size so that it can be inserted by the trocar. It is required that the movement of the robot does not interfere, hinder or add difficulty to the procedure performed by the surgeon, the movement of the robot must be natural, as a consequence of the interaction of the doctor with the tool.

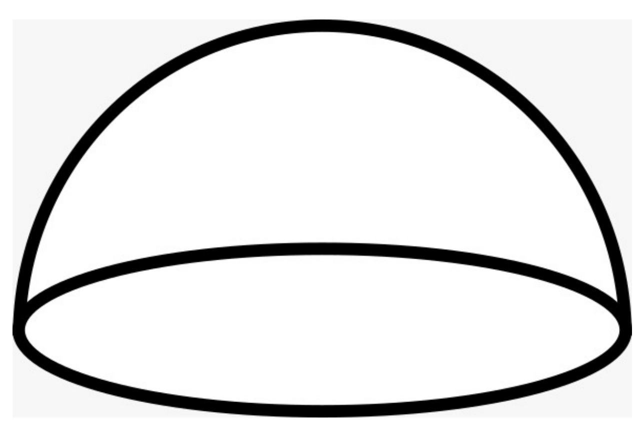

Fig. 2. Hemisphere.
Source: Authors.

Fig. 3. UMH Laboratory.
Source: Authors.

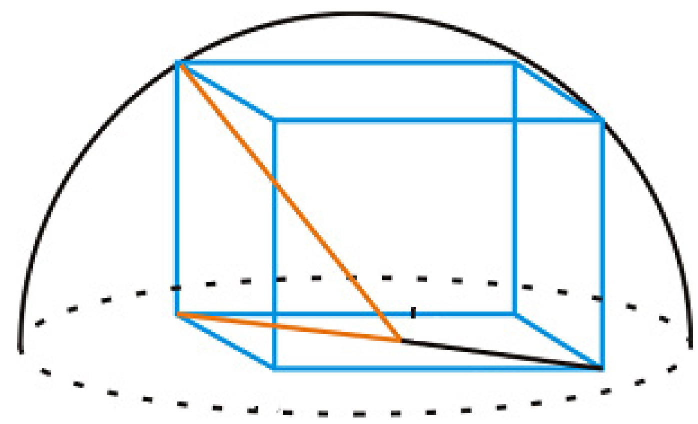

Fig. 4. Representation of the two scenarios.
Source: Authors.

As the work space is small, two movement alternatives are proposed: one is to illuminate the dark areas left by the endoscope and the other is to automatically identify the dark areas without depending on the endoscope. Given this, it must be taken into account where the lighting mini robot should be located to achieve these movement alternatives. For the first, the location of the lateral part of the hemisphere is used and for the second in the valley of the hemisphere.

The first movement is called geometric because the movement of the robot is the result of a function in space dependent on the movement of the endoscope, and the second will be automatic because it is the result of the identification of the darkest area and does not depend directly on the movement of the endoscope.

B. *Graphic environment design*

A graphic environment has been created that simulates the inside of the abdominal cavity with a liver and a gallbladder. This is affected by a new type of lighting caused by the set of lighting type mini robots, which creates new challenges compared to traditional lighting performed with an endoscope.

In order to simulate the behavior of the new lights and how they affect the scene, one must have characteristics that are close to reality, such as the color of the organs, the brightness of the ambient light or the roughness of the lower layer of the abdomen.

1) *Blender*

To make the base of the stomach and organs, the Blender program was used, a free open source software that serves, among others, to model, design and animate three-dimensional graphics.

The central objects of the environment are a liver and a gallbladder that are located on a rough layer that simulates being the bed of the abdominal cavity. In addition, three lights were added representing two fixed lights (which can be moved to a desired location) and one mobile (Fig. 5).

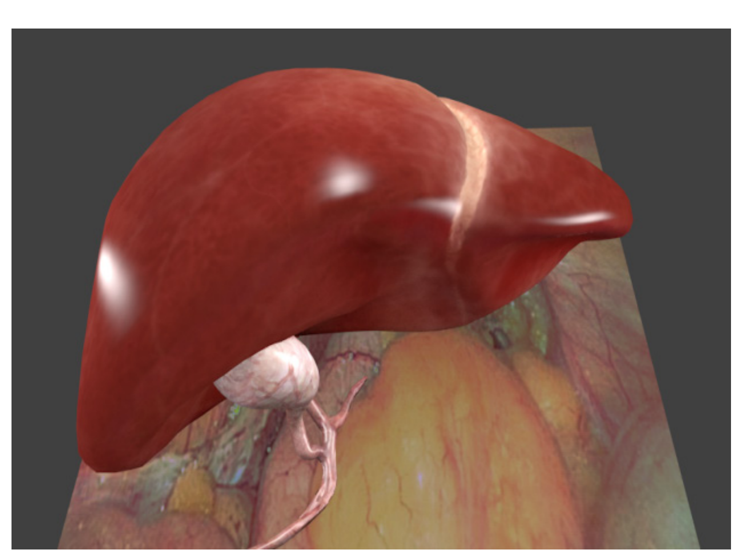

Fig. 5. Liver, gallbladder and base in Blender.
Source: Authors.

2) *Unity3D*

Unity3D is a cross-platform game engine. It has been designed to create video games and simulations. It was chosen to make the software tool because its physics engine can be very realistic, it supports 2D and 3D graphics and it is compatible with Blender, so it was possible to take advantage of the design work done previously.

In Unity all the necessary features of the surgical scene can be added.

C. *Description of the scene in Unity3D*

1) *Inside the abdominal cavity*

The liver and gallbladder were chosen because one of the operations most performed by laparoscopy is cholecystectomy, which consists of the removal of the gallbladder. The interior of the stomach is made up of the following elements:

- *Base*: Which has a texture that mimics the inside of the abdomen. This base has small reliefs to give realism to the scene, especially during lighting, as these reliefs or folds cause shadows. The size of the base designed in Blender is equal to the size of the acrylic base used in the UMH laboratory (Fig. 3), which was measured in the same laboratory and has dimensions of 35 cm wide by 45 cm long.
- *Liver*: Designed in Blender based on a conventional liver. The texture corresponds to a healthy liver.
- *Gallbladder*: Designed in Blender. It corresponds to a conventional and healthy gallbladder.

2) *Ilumination*

It consists of the light from the conventional endoscope (c), the light from the mini robot that was added as a proposal for this work (b) and two more lights that can be initially fixed on the sides of the stomach (a1 and a2). The location of these lights in the Unity scene is shown in Fig. 6.

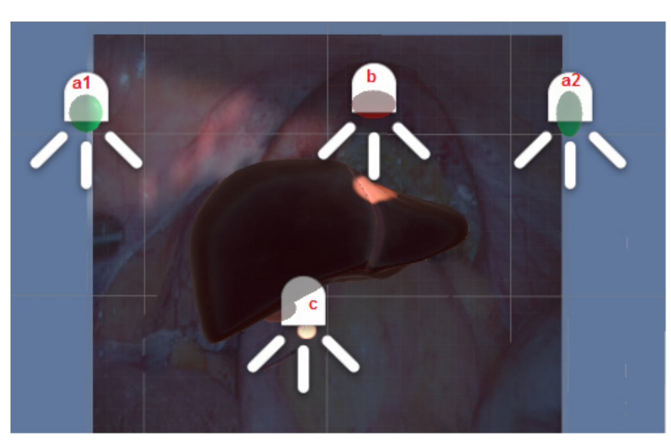

Fig. 6. Location of lights in Unity.
Source: Authors.

- *Endoscope:* The light that can be manipulated in the scene corresponds to the endoscope. This is operated with the keyboard and represents the conventional light used in laparoscopic surgery. In this case, only light is seen, since the endoscope was not physically represented (Fig. 7).

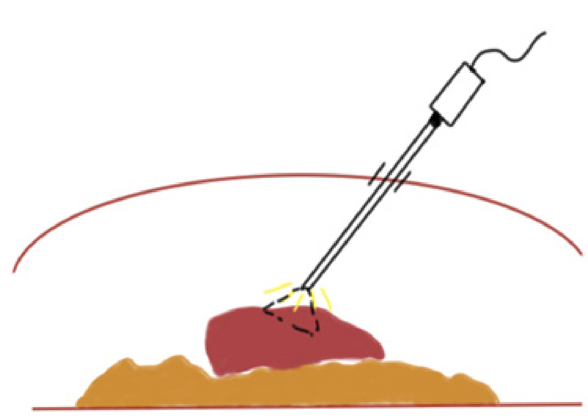

Fig. 7. Representation of the endoscope in a laparoscopy.
Source: Authors.

- *Lighting mini robot:* It is the new light added in this project. It is magnetically attached to the abdominal wall using a UR5 robotic arm that supports the mini robot from the outside of the abdomen. This mini robot offers a new lighting that supports the surgeon during the operation (Fig. 8).

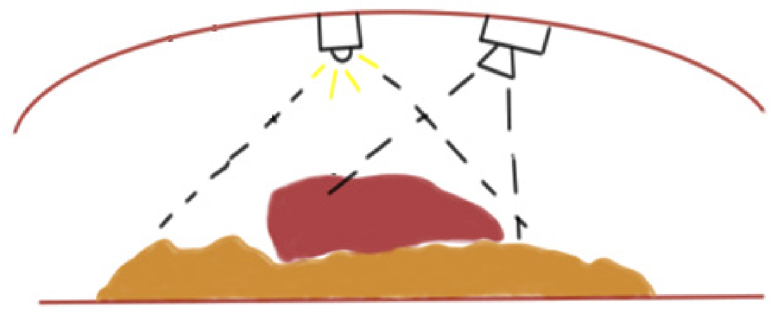

Fig. 8. Representation of magnetically held lights.
Source: Authors .

- *Camera:* Allows you to have a point of view similar to that of the surgeon during a conventional laparoscopy. Through this camera, a small space of the surgical scene can be seen. Its movement is independent of the movement of the endoscope and the mini robot. The image it takes can be seen on the right side of the interface.

3) *Interface windows*

Through these, the actions that take place within the scene and that are affected by image analysis or elements that represent what happens inside the simulated stomach are observed..

- *User interface window*: Through this window (Fig. 9) the interior of the surgical scene can be seen from a distance. It contains the buttons to manipulate the characteristics of the scene and allows you to see the different lights that are represented by colored spheres.

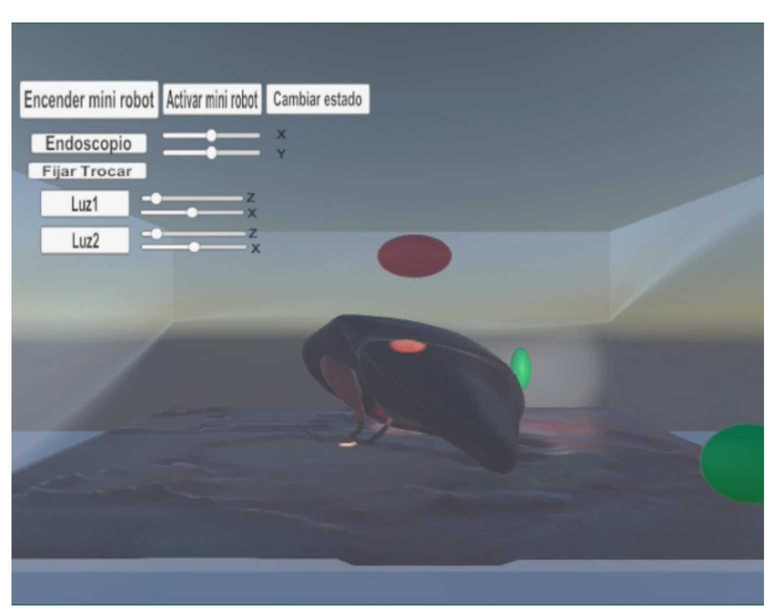

Fig. 9. Graphic interface.
Source: Authors .

The red sphere represents the light from the mini robot, while the two green spheres represent the fixed side lights.

The buttons allow you to turn on the lights, pause the movement of the mini robot or change the state of the movement.

With the WASD keys, the endoscope light can be moved with the turning effect that the trocar would give it. These keys and not the keyboard arrows were chosen for convenience to manipulate the tool, since in this case the use of the mouse and keyboard is required to manipulate all the characteristics of the scene.

The user's camera can be moved with the mouse in all directions, rotated, and away from the scene.

- *Window of the abdominal cavity*: This window (Fig. 10) shows the simulation of the abdominal cavity from a surgical point of view, this is why only part of the organ is seen, since in conventional laparoscopic surgeries the point of view of the endoscope it is not very wide (Fig. 11).

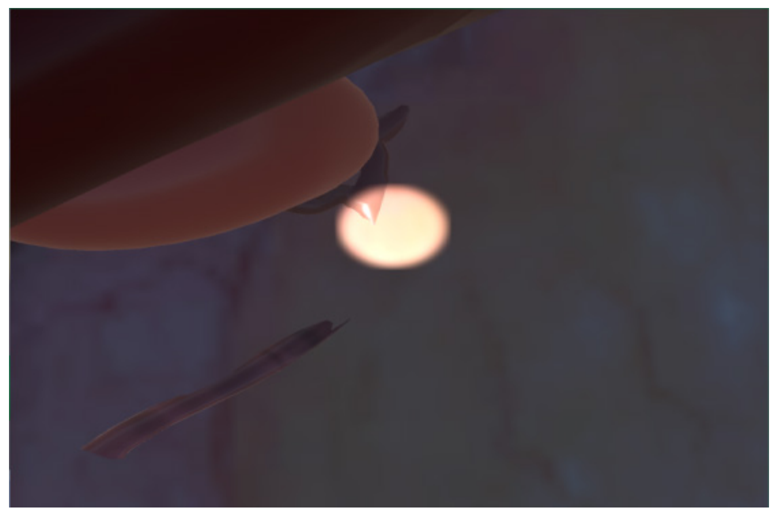

Fig. 10. Window of the abdominal cavity.
Source: Authors.

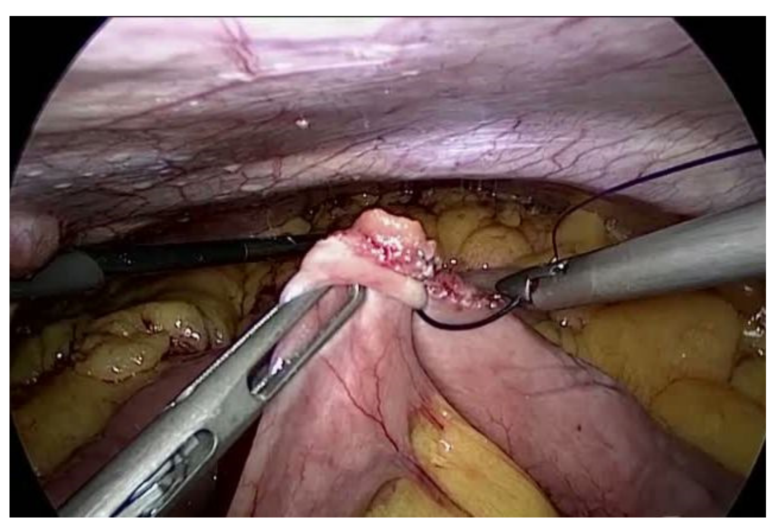

Fig. 11. Conventional laparoscopic surgery point of view.
Source: [55].

D. *Funcionamiento de la herramienta software*

The software tool allows to manipulate the mentioned elements in such a way that the user can move the endoscope, the mini light robot, the fixed lights and the camera. The tool was developed in Unity3D and the C # and Python languages were used in addition to the OpenCV library for computer vision.

This tool aims to improve the lighting within the abdominal cavity by using the mini light robot, which has two types of behavior, a geometric movement dependent on the movement of the endoscope and an automatic movement that illuminates the darkest section of the scene. The angle at which the mini robot is located with respect to the scene is inclined (as it follows the endoscope) for geometric movement and perpendicular to the upper face of the hemisphere for automatic movement.

1) *Geometric movement*

This movement is established under the premises mentioned in section III a: tool overview.

The lighting mini robot moves on a circular path where the angle α, which indicates the position, is associated with the movement of the endoscope. Equations 1 to 5 show the calculation of this angle and represent the movement of the mini robot on the circumference. This in order to provide complementary lighting, illuminating the remote areas to the light provided by the endoscope. For this, the geometric coordinates where the robot will make its movement are calculated (Fig. 12).

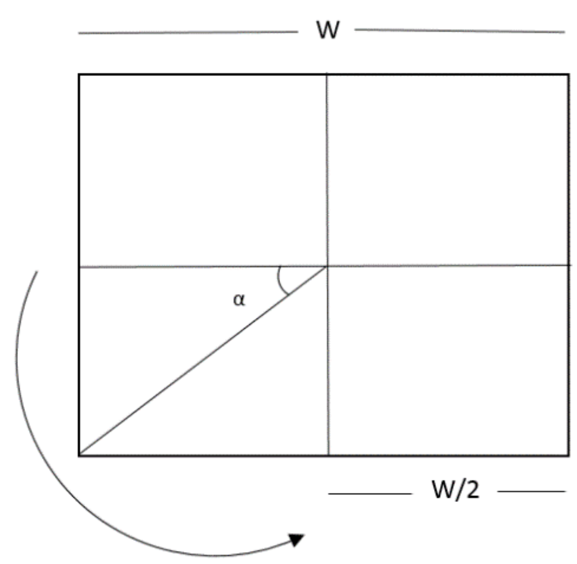

Fig. 12. Calculation of equations.
Source: Authors .

When the endoscope moves to the right, the robot rotates to the left and vice versa.

$$radius = constant \tag{1}$$

$$\alpha = \left(x * \frac{\pi}{2}\right) / \frac{W}{2} \tag{2}$$

$$C_x = -radius * \cos\alpha \tag{3}$$

$$C_y = radius * \sin\alpha \tag{4}$$

$$C_z = known \tag{5}$$

From the above, w is the image that the user sees and is known, *radius* corresponds to the radius of the circumference of the abdomen, and Cx and Cy represent the position coordinates of the light in the XY plane. Cz corresponds to the height and, like the *radius*, is known and is related to the dimensions of the stomach. In this case it is constant for simulation purposes, but in a conventional abdomen it should be taken into account that the height changes because the surface is curved. Finally, x is the position of the endoscope, so it is variable.

Once the coordinates are obtained, the lighting mini robot is moved in such a way that it illuminates a complementary area, which remains dark when the endoscope is moved away (Fig. 13).

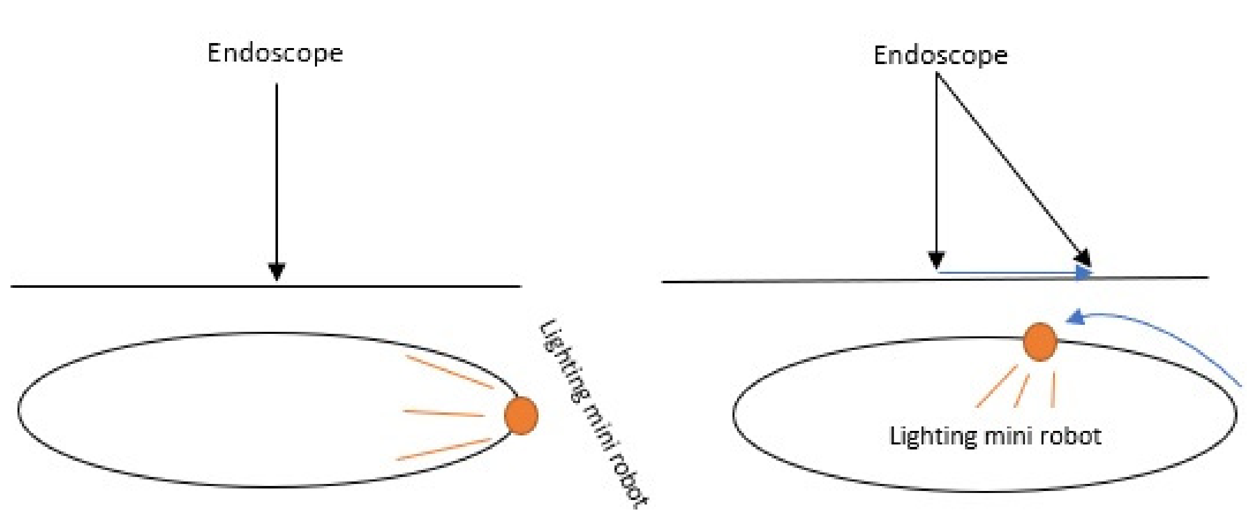

Fig. 13. Geometric movement scheme.
Source: Authors.

2) *Automatic movement*

With this movement, the lighting mini robot illuminates the darkest point in the scene, regardless of the movement of the endoscope. This movement is directly linked to the image analysis because it is through this analysis that the darkest point will be found. To get the lighting mini robot to automatically move to a certain point, the images of the surgical scene must be analyzed. To achieve this, the first step is to capture the image of the visible screen (ViewHolder). This image corresponds to the space visible by the endoscope camera (Fig. 10), where a total image of the camera is captured, each time the image processing in Python ends, which is stored in the local directory for its analysis.

Once the image is stored, the darkest point is identified, for this the image is transferred to grayscale and its respective histogram is obtained. The histogram is a graph that gives a general idea about the intensity distribution in an image [56], [57], [58]. The histogram is calculated the percentage of light to know which is the darkest area of the image.

To achieve this, the grid pitch S is calculated (6).

$$S = \sqrt{\frac{N}{k}} \tag{6}$$

Where N is the number of pixels (width × height) and k is the number of regions to be divided into. Then the points (x, y) of each region are obtained and the histogram is calculated. Equation 7 is applied to the histogram.

$$L_{k=\sum_{x=0}^{255}\frac{N_x}{T_s}*X_p} \tag{7}$$

Where L is the percentage of light in an area k, X the position in the histogram, Nx the number of pixels assigned to the intensity of the light X, Ts the total of pixels in the position k and Xp the percentage of light of the position X in the histogram.

Finally, each center is assigned the percentage of light L.

The darkest point (x, y) is only obtained when the scene image has been captured or if the image conditions (lighting) have made that point no longer the same. Once the dark point in the image is identified, we proceed to calculate its coordinates in the 3D scene (a, b, c). For this, the ViewHolder point is projected on the stage and the coordinates are calculated in two-dimensional space (Fig. 14). The transformation of coordinates is performed because the robot moves in a 3D world and the darkest point is identified through a plane that is the screen observed in the ViewHolder. In other words, the darkest point identified in the ViewHolder is projected on the AB plane of the three-dimensional space that represents the abdomen.

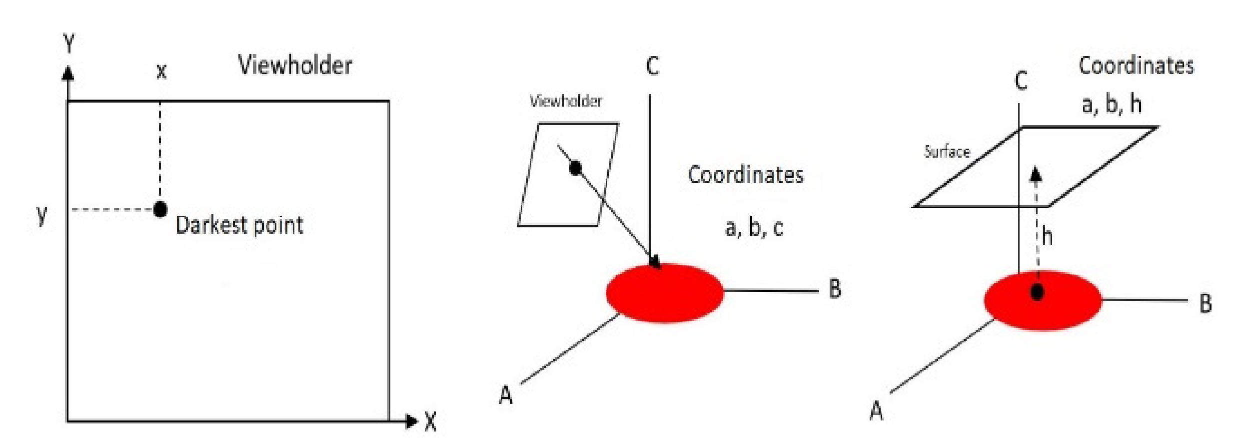

Fig. 14. Coordinate projection.
Source: Authors.

With the calculated coordinates, the robot is moved on the surface of the abdominal cavity, so it only moves in the AB plane ignoring the C coordinate. This movement will occur every time there is a new dark point according to the illumination of the scene and camera movement.

III. Tests and Results

A. *Motion tests*

Tests were carried out with the software tool to observe the movement of the lighting mini robot in changes in lighting and in the movement of the endoscope. Likewise, tests were carried out with a representation of the real environment.

To show the location of the lights on the image of the abdominal cavity, a 10 × 10 grid will be used to act as a quadrant of a plane. With the help of this grid, points can be used to locate the endoscope and record the location of the mini light robot in the two types of movement: geometric and automatic. This grid is used to size the test (Fig. 15).

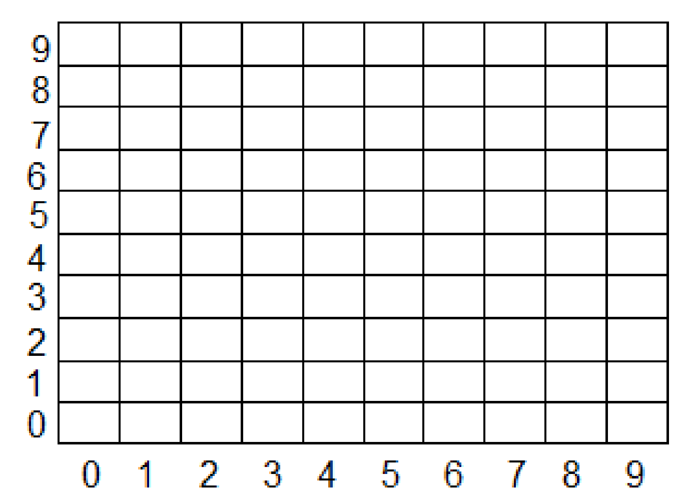

Fig. 15. Grid to size the tests.
Source: Authors.

The movement of the abdominal cavity camera can cause changes in lighting, which will create a new image that will allow new dark spots to be illuminated. Schemes of the grid will be shown indicating the points where the different lights are located.

The endoscope moves close to the gallbladder, below the liver because it is an area of greater interest since it allows to illuminate this organ and its surroundings, taking into account that the tool was designed with the procedure of removing a gallbladder in mind.

In the following graphs, the yellow points represent the light of the endoscope, the orange points the light given by the geometric movement, the blue points the light given by the automatic movement and the green points the light of the mini robot with automatic movement in the representation of the real environment (Fig. 16, Fig. 20, Fig. 22, Fig. 24, Fig. 26, Fig. 28 and Fig. 30).

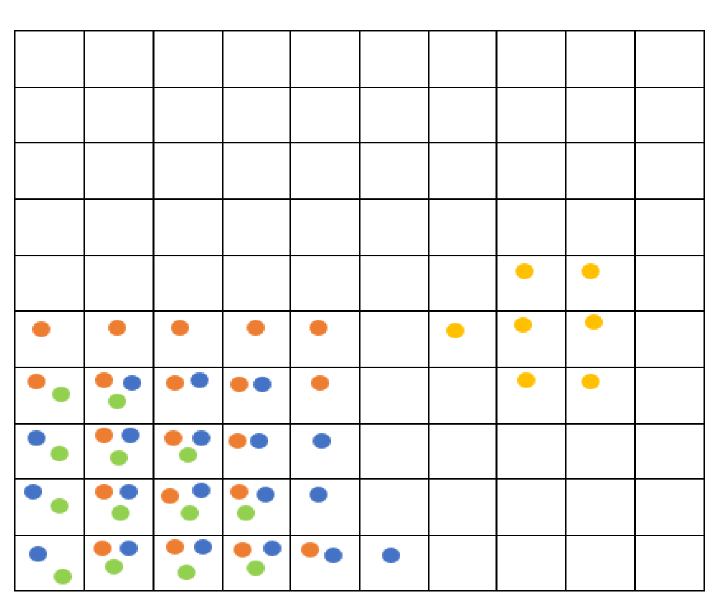

Fig. 16. Representation of the lights on the grid. Schematic representation of test 1.
Source: Authors .

For the representation of the real environment, tests similar to those of the software tool are carried out, but this time using photos of a representation of the same and testing only the automatic movement since it is this movement that was designed for tests in a real environment. In this case, geometric movement is not used because it was not intended for real tests and because it is a movement that depends on the endoscope, something that is not present in the representation of the real environment. Each photo was manually put into the tool's code. These photos undergo the same image analysis as the screenshots, allowing the mini light robot to move to the darkest point.

This stage was built by hand using red, black, white and orange plasticine and an eighth of 35 cm × 25 cm straw cardboard (Fig. 17). To achieve the necessary lighting conditions, a medium conventional flashlight was used that was chosen because the light was more similar in color and shape to that of the tool. In the test figures you will see the light in the actual experiment and the light in the tool. A 50 cm × 40 cm 15.5 cm tall rectangular shaped cardboard box was also used to help with lighting conditions.

Fig. 17. Scenario built as a representation of the real environment.
Source: Authors.

B. *Results*

The grid diagrams in the previous section allow observing the behavior of light for the two movements: geometric and automatic, and for automatic movement with the images of the representation of the real environment. With this it is evident that generally both the geometric movement and the automatic movement illuminate similar portions in the scene.

Geometric movement is more "sensitive" since it depends on the movement of the endoscope, which makes it illuminate more and different areas than the automatic movement. The algorithm of automatic movement will not allow the mini robot to illuminate another region unless there are significant changes in lighting, this is evidenced in Fig. 18, Fig. 19 and Fig. 21.

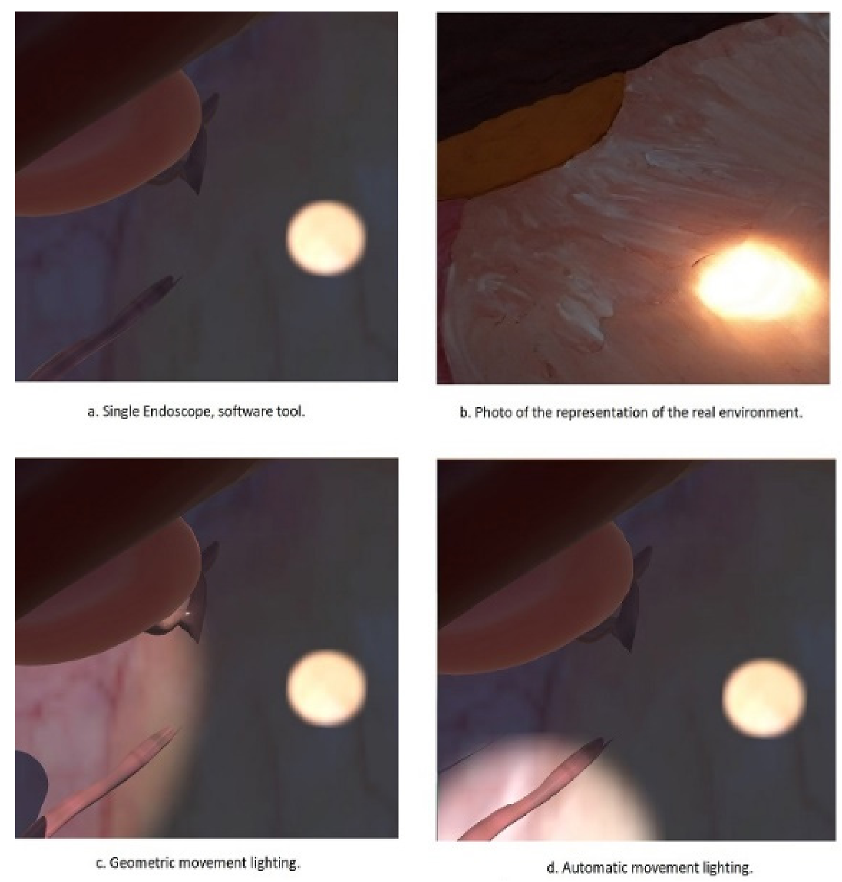

Fig. 18. Lighting test 1.
Source: Authors.

Fig. 19. Lighting test 2.
Source: Authors.

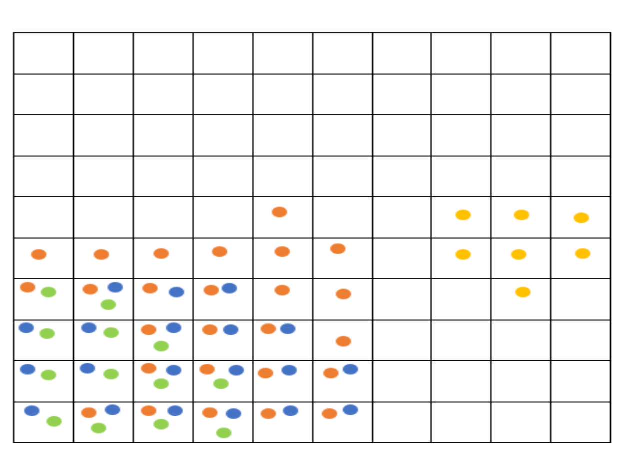

Fig. 20. Schematic representation of test 2.
Source: Authors.

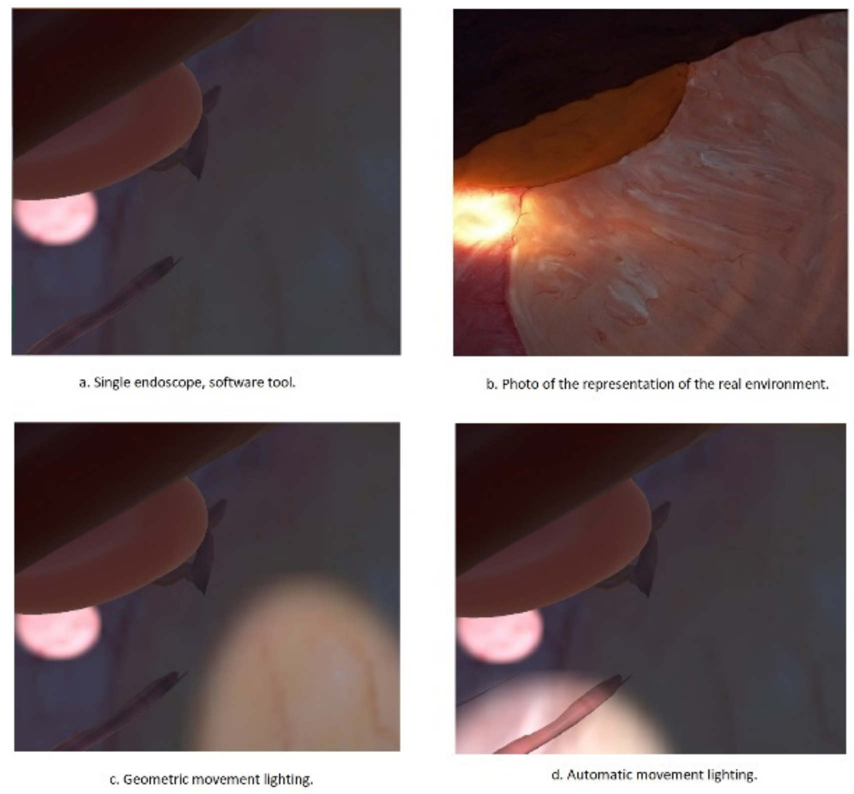

Fig. 21. Lighting test 3.
Source: Authors.

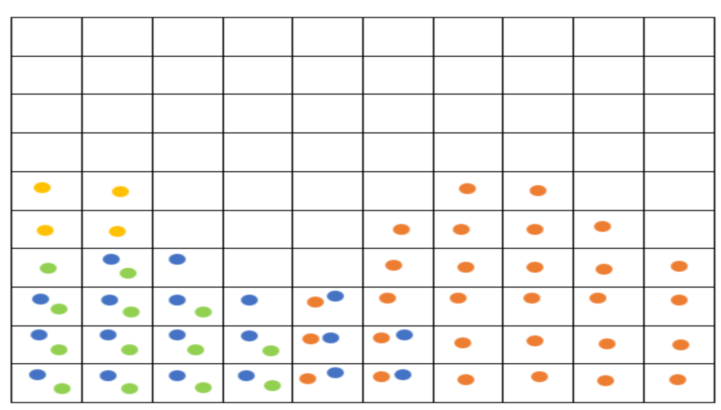

Fig. 22. Schematic representation of test 3.
Source: Authors.

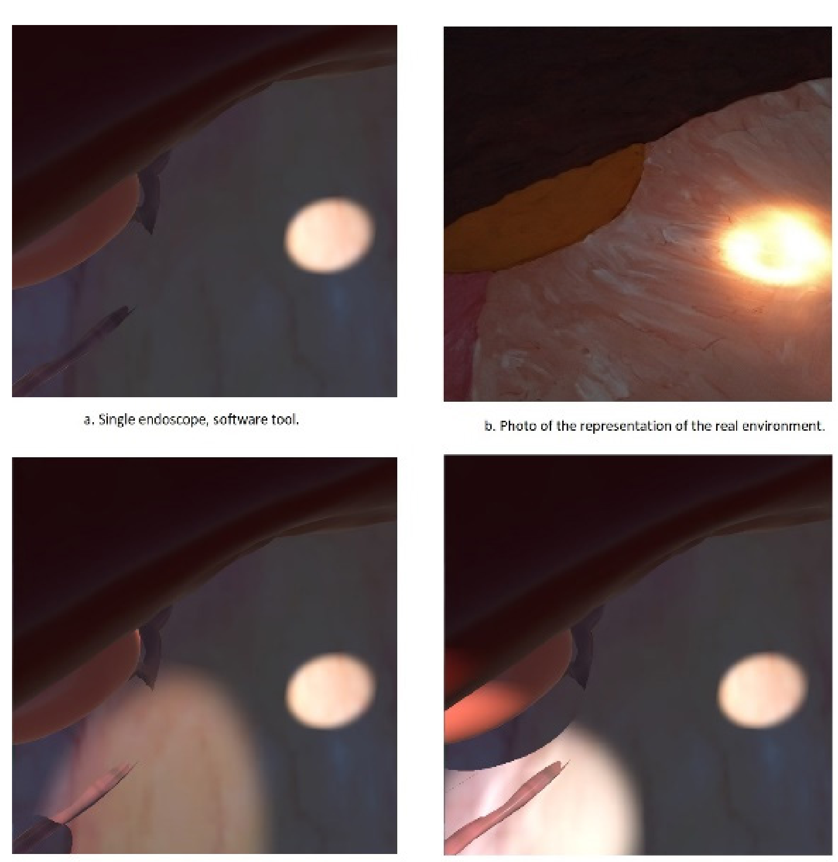

Fig. 23. Lighting test 4.
Source: Authors.

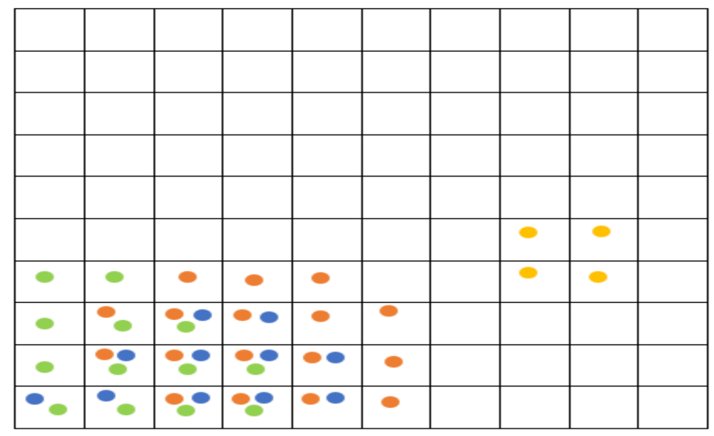

Fig. 24. Schematic representation of test 4.
Source: Authors.

To generate significant lighting changes in the surgical scene, not only the endoscope must be moved but also the camera's point of view must be changed, by doing this the algorithm will detect new dark spots. (Fig. 25, Fig. 27 y Fig. 29).

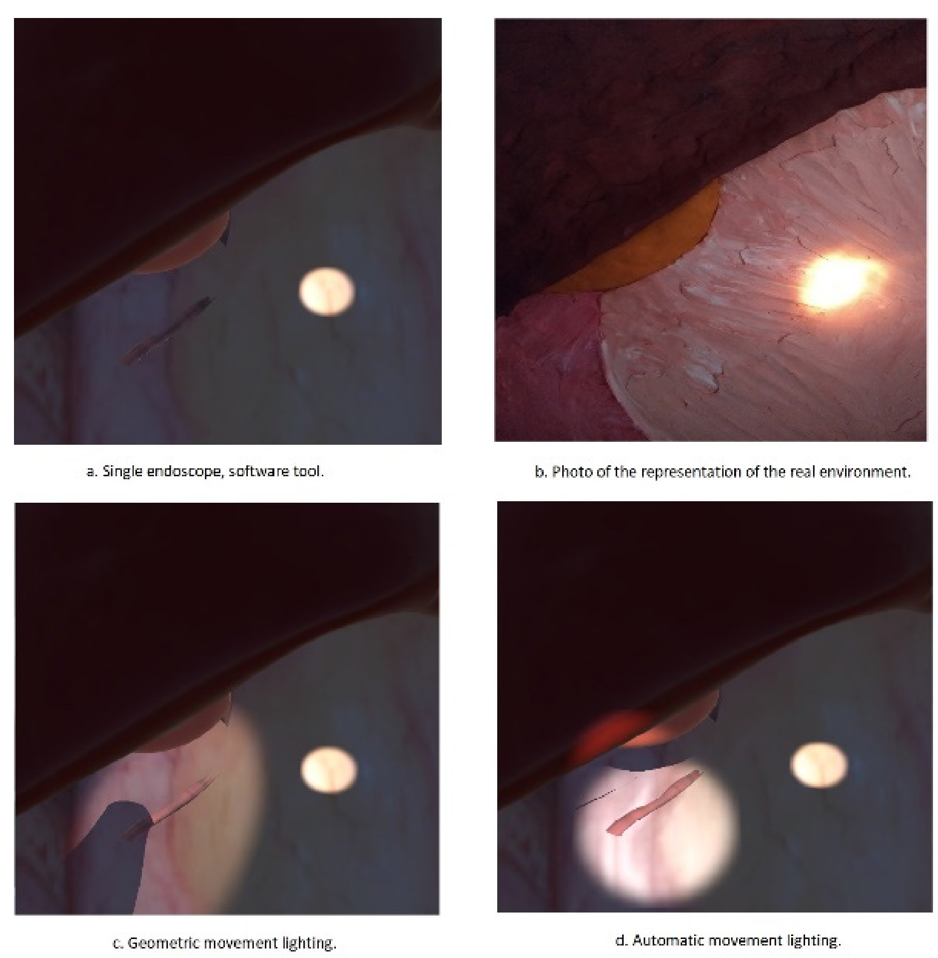

Fig. 25. Lighting test 5.
Source: Authors.

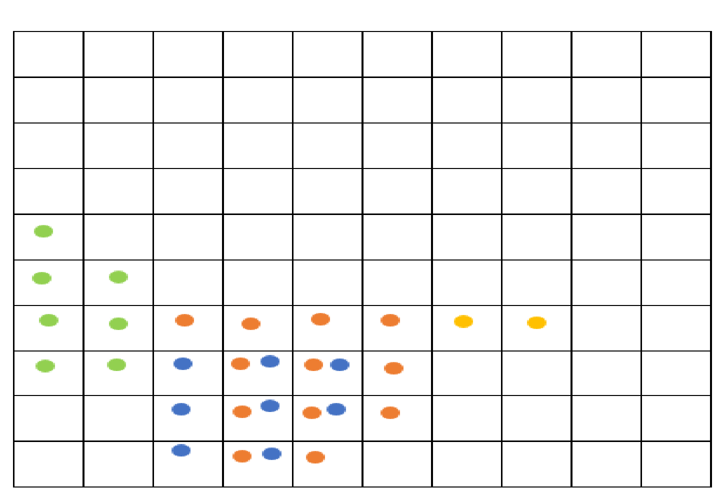

Fig. 26. Schematic representation of test 5.
Source: Authors.

Fig. 27. Lighting test 6.
Source: Authors.

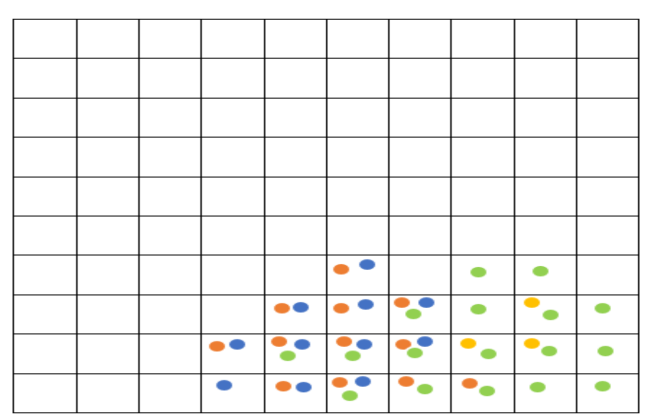

Fig. 28. Schematic representation of test 6.
Source: Authors.

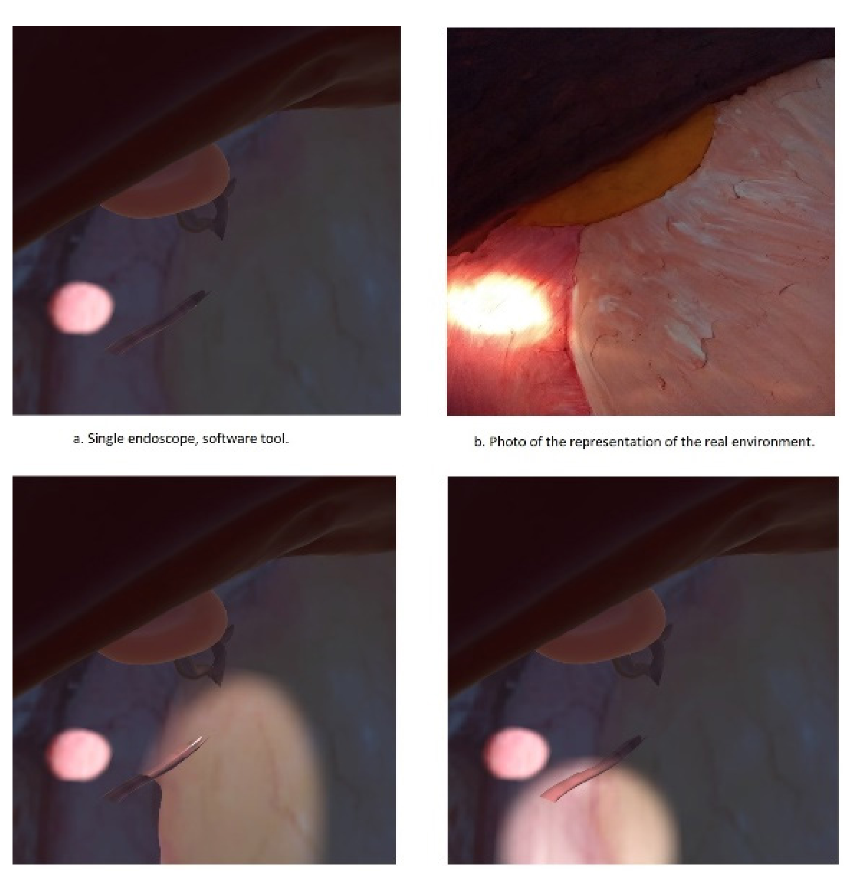

Fig. 29. Lighting test 7.
Source: Authors.

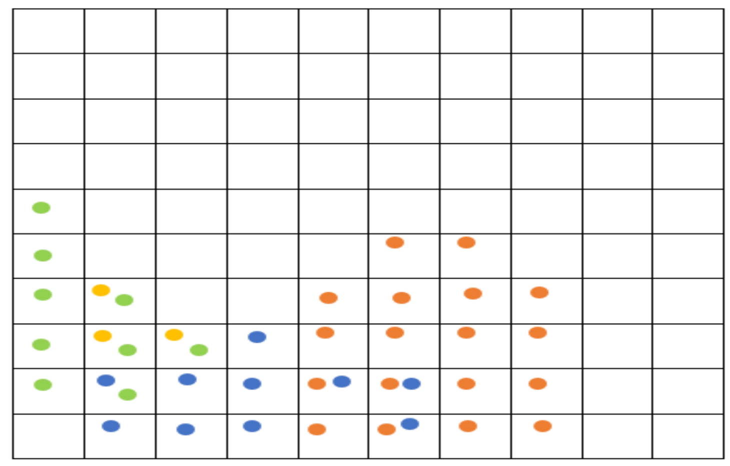

Fig. 30. Schematic representation of test 7.
Source: Authors.

This shows that the geometric algorithm can cover more areas, but depending on the movement of the endoscope, when it is not moving the mini robot does not move to illuminate any point. It should be remembered that both the endoscope and the mini robot can be turned on and off from the tool explained in section III b: graphic environment design. In these cases the mini robot would only illuminate with the automatic movement.

In two tests (Fig. 21 and Fig. 29) a difference in the illumination of the two movements was evidenced. In these images it is observed that the geometric movement illuminates one side of the scene while the automatic one illuminates the opposite side, although on the same axis. This matches the location of the endoscope on the left side of the screen..

In general, taking into account the exception mentioned in the previous paragraph, most of the tests showed that both movements allow to illuminate the same areas, although the intensity of the light and the coverage are different in each movement. That is, for the geometric movement the light is wider but less intense while for the automatic movement the light is more intense but the coverage area is smaller, this is mainly due to the angle at which the mini robot is located as mentioned in section III d: operation of the software tool.

The illumination achieved with the representation of the interior of the abdominal cavity to observe the behavior of the software tool before an image with real lighting conditions is presented in Fig. 16, Fig. 20, Fig. 22, Fig. 24, Fig. 26, Fig. 28 and Fig. 30. These show that generally the mini robot would illuminate areas similar to those of the tests with the simulated environment. There are some noticeable differences that may be due to the more realistic nature of the image. It should be noted that the photos chosen are as similar as possible to the images of the tests carried out with the software, although they do not refer to an exactly the same representation.

In simulation, the advantages of each movement are evident in the various tests carried out. Also, it can be said that the movement generated by the geometric algorithm provides better lighting and reaction over time with respect to the other, although there is less control over what is being illuminated.

IV. Conclusions

This article showed the implementation of a simulation algorithm that allows an abdominal scene to be adequately illuminated in laparoscopic operations. This abdominal scene was constructed using the Unity 3D graphic engine, where the main organs of the abdomen can be seen and where the illumination comes from two fixed lights and the light from the endoscope. The algorithm designed allows a mini robot that would be magnetically anchored to the abdominal wall, to move to low-light areas following two options: either a geometric relationship with respect to the position of the endoscope light, or a movement as a result of an image analysis that reveals the darkest areas of the environment.

The results show that both the geometric and the automatic movement fulfill the same function of providing extra lighting and in general, with some exceptions, they coincide in the areas they illuminate. The geometric movement seems to cover more area because of the angle the mini robot is at. For its part, the automatic movement, which depends on image analysis, is updated when the algorithm finds a new dark point.

The two algorithms were tested in the designed tool and for the one dependent on the image analysis, a plastic model was also used. For this last case, photographs were taken that were passed to the image analysis algorithm, and their result was compared with that given by the tool.

The behavior of the tool in a real setting may vary due to the characteristics of the lighting and even the organs or objects to be illuminated. Several aspects must be taken into account such as external light, the color of the light, the type of camera, among others, and whether it involves tests in a laboratory such as the UMH or in *in or ex vivo* tests.

Finally, it is shown that the two options provide better illumination of the area to be operated on, illumination that can be placed at will by the surgeon if necessary. The behavior of the system shows the contribution that lighting mini robots can provide by providing extra lighting that, operating autonomously, provides the medical specialist with a better view of the area to operate when necessary.

Future works will test these algorithms with a real robot arm and a test box, in order to evaluate the functionality of the entire assembly. In this case, the robot arm will hold the mini light robot using MAGS technology, which would be introduced into the test box through a trocar as in conventional laparoscopic surgery.

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