DEVELOPMENT OF AN AUGMENTED REALITY SIMULATOR FOR A ROBOTIC SYSTEM USED IN SINGLE INCISION LAPAROSCOPIC SURGERY

CALIN VAIDA , GABRIELA RUS, BOGDAN GHERMAN, ALEXANDRU PUSCA, PAUL TUCAN, IONUT ULINICI, DOINA PISLA

Abstract. Augmented Reality (AR) became a very useful tool for various domains, with multiple applications in different medical fields, where this technology is integrated in medical training, image-based diagnosis, simulation of medical tasks, or in guiding systems for surgical procedures. The introduction of AR technology in robotic assisted surgery is relatively new and challenging considering the required precision for this type of medical task. The objective of this study is to develop an AR simulator for robotic assisted Single Incision Laparoscopic Surgery (SILS) where the robot performing the procedure is embedded in a virtual environment, providing both an interactive training and a simulation environment. The architecture and particularities of the proposed robot for SILS are analyzed for a better understanding of the structure, to obtain the validation of the kinematic model. The final result is represented in the form of an application which can be operated with Hololens 2 device.

Key words: robotic assisted SILS, augmented reality, kinematics, AR simulator, Hololens 2.

1. INTRODUCTION

Augmented Reality (AR) is defined as the technology which combines a virtual world with the real one [1–2]. Compared with Virtual Reality (VR) which is fully immersive, AR technology augments reality, enhances the physical world with digital components in a non-immersive environment. The AR concept was discussed for the first time in 1950, when cinematographer Morton Leonard Heileg, who was fascinated with 3-D movies, studied both the human sensory signals and illusions in order to develop what he called “a cinema of the future”. The first prototype of his idea, named Sensorama, was also developed by M. Heileg in 1962, being a huge machine, which integrated different sensory inputs

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such as: changing temperature or audio stimuli [3]. From 1962 to the present day, many people were attracted to the idea of integrating a virtual world into our physical world, so the devices developed during this period became more and more intuitive, smaller, and technologically advanced.

During the last decades, due to the evolution of AR devices, this technology has been implemented in many sectors such as: education, entertainment, and healthcare.

The high potential usage of the augmented reality technology in medical field was observed from early stages, being used especially for training, image interpretations and therapies for patients. AR has also been used with success in surgical procedures where a good visualization of anatomy in preplanning phase and intra-operative phase is crucial.

In medicine, robotic systems started to be used 40 years ago, their role and task becoming more complex with the progress of technology. A special category refers to the robotic systems which are actively used in different procedures where they interact directly with the patient (called clinical robots), performing tasks where they surpass the natural capabilities of human beings. In invasive scenarios, such as surgery or oncology, the robots act as highly dexterous and advanced tools with “zero” autonomy, fully controlled by a doctor in a master-slave architecture. Surgical applications involve complex multi-arm robotic systems for general, minimally invasive procedures [4], or simpler ones for the manipulation of tools, as in knee arthroplasty [5], or the positioning of the endoscopic camera [6]. Other minimally invasive techniques are targeted oncologic diagnosis [7] and treatments like brachytherapy [8] or ablation [9].

A typical minimally invasive surgical procedure involves the insertion of the surgical instruments through several small incisions along with an endoscopic camera which provides intraoperatory images. An even less invasive approach is the Single Incision Laparoscopic Surgery (SILS) which involves the insertion of surgical instruments through a single incision inside the patient body. The use of this treatment resulted in a faster recovery, less post-operative pain, a shorter stay in the hospital, and a lower use of analgesics. The process involves a single incision through which the trocar is placed, followed by the placement of instruments [10].

Despite the specific advantages of SILS, this procedure presents a series of drawbacks which could not been neglected such as the incommode position of the surgeon during the operation (above the patient), low dexterity and precision, hand tremor [11] or the limitation of the range of motion since the active instruments and the endoscopic camera are situated in the same port [12]. To offer a solution for these weaknesses, robotic systems for SILS were developed. The advantages of using robots in single incision laparoscopic surgery are presented in [13], and include excellent accuracy, repeatability, and the ability to work in a limited operating field enabling the use of highly dexterous instruments with multiple bends [14–16].

The utilization of AR in SILS aimed especially the preplanning phase, where the surgeon has the possibility to visualize and interact with the target organs, which are reconstructed from CT/MRi images. This subject is discussed in detail in [17], where the advantages of using augmented reality in preoperative planning and training are highlighted. The technological advance from the last decade, enables the introduction of augmented reality in almost every step of the surgery process. In present, many studies [18–21] illustrate the utilization of AR to visualize the target anatomy, to identify important structures or for tracking based on markers. In [22], the authors proposed the utilization of AR both in preplanning phase and intra-operative phase to enhance the robotic assisted surgery. The suggested system is composed of an AI/AR module and has the aim to assure a superior procedure by using the module for the training process, pre-planning stage, and intraoperative phase where the module could trigger hazard warnings.

As it can be seen the implication of augmented reality in SILS procedures has been studied and analyzed in many articles, where different AR devices were used to visualize a target anatomy during the planning or intraoperative phase, therefore the AR utilization in SILS is especially focused on the surgery procedure, neglecting in this way the aspects of the robotic assisted SILS.

The main goal of this paper is to offer a new perspective on applications of augmented reality in robotic assisted SILS. In the development of innovative robotic systems, AR can contribute to the efficient design, structural optimization, the study of multiple configurations with respect to different tasks, all these being performed in an interactive environment where the user can even interact directly with the digital equipment.

Thus, the authors will present, an AR simulator for a robotic system used in single incision laparoscopic surgery which enables the user (1) to visualize different simulations achieved on surgery specific motions and (2) to interact directly with the robotic system environment.

Following the introduction section, Section 2 describes an analysis of different methods to develop an augmented simulator for robotic assisted medical application. Section 3 describes the architecture of the developed simulator, followed by Section 4 where the simulator is used to validate the mathematical model. The results and the conclusions are presented in Section 5, respectively Section 6.

2. ANALYSIS OF DIFFERENT AR METHODS USED IN ROBOTIC ASSISTED MEDICAL APPLICATIONS

In order to provide quality services, robots' integration in industries like the automotive, construction, gaming, and medical sector have been demonstrated to be an ideal answer, improving the operation's quality and lowering the potential for errors. The developing process for a robot is complex and expensive, and any error in development phase could hinder the functionality of the robot. To reduce/eliminate these errors, many tools were created, one efficient tool being the software for 3D visualization or simulators, capable of creating a virtual environment for the designed robot, reducing in this way both the time for execution and the cost of developing. Simulators have the advantages to offer an adequate illustration of the mechanism, where all inaccuracies from design or mathematical model are identified and then avoided. Using simulators, the prototype can be improved to develop the best version of it.

The existing simulators for robots are focused on industrial robots, for which software like ROS (Robot Operating System) offer full support, including even an extended library of industrial models for robots. The most common method to create an AR simulator with ROS is presented in Fig. 1.

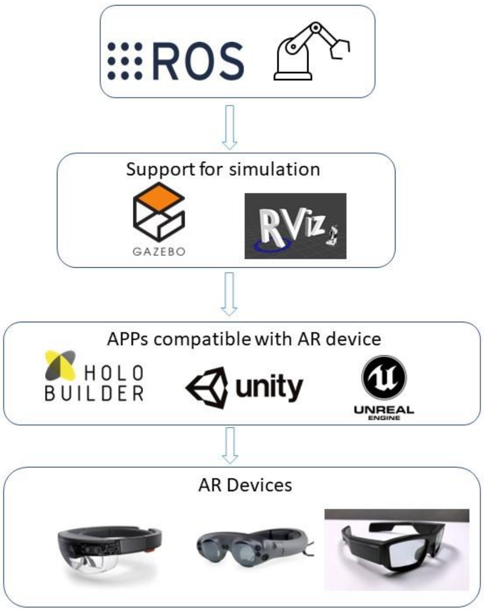

Fig. 1 – Schematic representation of an AR simulator with ROS.

Robot Operating System is usually utilized with other frameworks specialized in robotic simulations. The simulation can be transmitted to a specific 3D development platform that supports AR devices such as Unity or Real Engine. This platform must have the required infrastructure to support AR devices such as Hololens.

Due to the fact that ROS provides a vast collection of tools and packages designed to support the development of robots, it is widespread and used by many people from industry. However, the system has few limitations, one of them being that of being primarily oriented to industrial robots.

Although is very common to use ROS and Gazebo for simulators, there are more platforms which provide the possibility to create a simulator for robots. The most known platforms are presented in Table 1.

Table 1

The most known platforms dedicated to simulations for robots [23]

Robotics simulation applications
MATLAB - Robotics System Toolbox
V-Rep
ARgOS Simulator
Unity 3D
Webots
Robo DK
Coppelia Sim
OpenRave

These platforms provide features such as algorithms for collision detections, trajectory generation, forward and inverse kinematics and so on. Despite of evidence benefits, these platforms have also constrains considering the development of an AR simulator for robots. The major limitation for most of them is the lack of support for augmented reality, which means that the creation of an AR simulator with these platforms require another intermediate platform which supports augmented reality. Exception is Unity 3D which provide an adequate support for this type of technology.

Taking into account these aspects, Unity represents an adequate alternative because is not oriented to industry or any other specific domain, but it offers a valuable support for simulation of any kind of robot and offer a great support for AR.

3. ARCHITECTURE OF THE DEVELOPED AR SIMULATOR

Even though robotic assisted surgery became popular in 2000 with Da Vinci robot [24], the simulators for medical robots remain a less explored topic, the simulation for surgeries being focused on classical procedures.

Due to the fact that SILS procedure requires a high level of accuracy and safety precision, taking into account the narrow operating space and preventing instrument collisions when performing the procedure as can be seen in Fig. 2, the development of a reliable robotic system is essential.

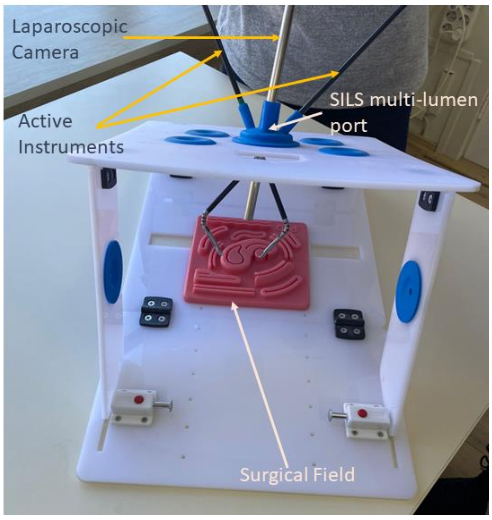

Fig. 2 – The configuration of surgical instruments and laparoscopic camera in a SILS procedure.

Based on the classical approach, CAD software like NX Siemens [25] and simulators as Gazebo can offer a realistic perspective of the mechanical construction of the robot as same as the limitations and constrains. In addition to this, the VR and AR technology offer for the developers the possibility to visualize the structure in full size. Furthermore, AR technology provides the option of integrating the robot in a real environment for improved visibility and comprehension of the requirements for a specific task.

Additionally, the AR simulator could be adapted to serve as an input for the direct control system of the robot, as can be seen in Fig. 3 where the gesture of user could be converted in coordinates for a real robotic system control, to activate it to position the mobile platform.

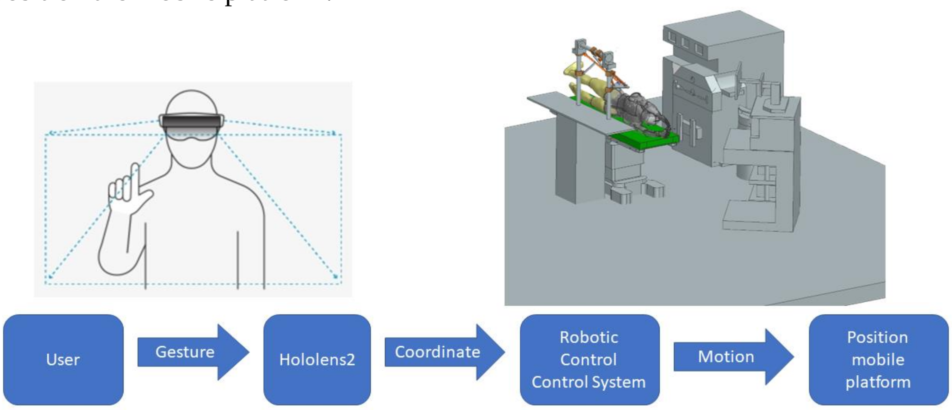

Fig. 3 – Integration of the AR simulator for control of the SILS robot.

3. 1. DESCRIPTION OF AN INNOVATIVE PARALLEL ROBOTIC STRUCTURE FOR SILS

The utilization of the parallel robots for SILS represent a valuable solution considering the stability of the parallel structures, providing an excellent accuracy for motion.

The robotic system presented in [26] is a parallel robot with 6-DOF (degree of freedom), which guides the specialized mobile platform. The platform contains a laparoscopic camera and two active instruments (with 3-DOF each) which are guided using RCM (Remote Center of Motion).

This approach avoids a series of drawbacks of other robotic systems, such as robotic arm collision and limited dexterity of instruments.

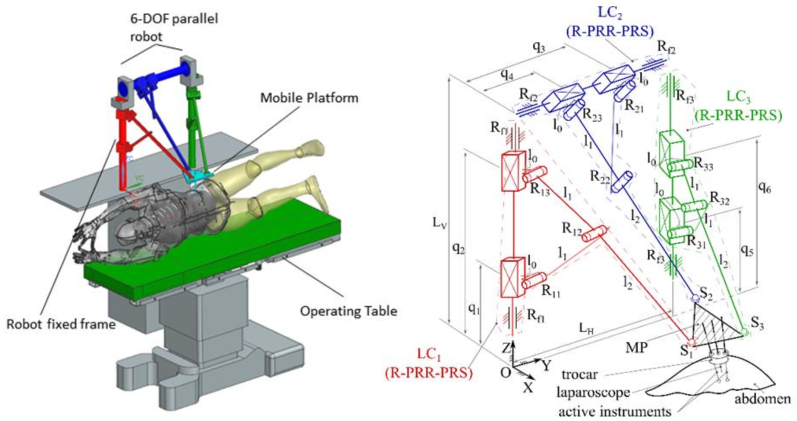

Fig. 4 – Parallel robotic structure for SILS:
a) CAD representation, b) the kinematic scheme [26].

In order to obtain an adequate perception for the tasks the robot should execute during the surgery procedure, a medical protocol was established with the support of medical experts. The protocol which is described in detail in [26] includes the preliminary stage where the diagnostic and the therapeutic conduit are established, the relative positioning of both patient and robot with respect for the target organ, the positioning of the mobile platform towards the insertion point, the insertion of the instruments, execution of surgical task, the retraction of the instruments and the movement of the robot in home position.

As can be seen in the kinematic scheme illustrated in Fig. 4, the parallel robot consists of three identical kinematic chains *LC1*, *LC2*, and *LC3* (type R-PRR-PRS) positioned in a rectangular configuration, each kinematic chain being actuated by the prismatic joints q_1 q_2 for LC_1, q_3, q_4 for *LC2* and q_5, q_6 for LC_3. Each chain has a passive rotation motion (R_{f1},R_{f2},R_{f3}) and three passive revolute joints : R_{11}, R_{12}, R_{13} for L_{C1}, R_{21}, R_{22}, R_{23} for L_{C2}, R_{31}, R_{32}, R_{33} for LC_3.

The mobile platform is connected to the kinematic chains through three passive spherical joints S_1, S_2 and S_3. The Cartesian coordinates of the spherical joints with respect to the fixed coordinate OXYZ, attached to the robot frame are presented in equation 1:

$$S_1:\begin{cases} X_{S1}=X_E+\frac{\sqrt{3}}{6}l_p\,c_\psi\,c_\theta-\frac{1}{2}l_p\,c_\psi\,s_\theta\,s_\varphi+\frac{1}{2}l_p\,s_\psi\,c_\theta \\ Y_{S1}=Y_E+\frac{\sqrt{3}}{6}l_p\,s_\psi\,c_\theta-\frac{1}{2}l_p\,s_\psi\,s_\theta\,s_\varphi-\frac{1}{2}l_p\,c_\psi\,c_\theta \\ Z_{S1}=Z_E-\frac{\sqrt{3}}{6}l_p\,s_\theta-\frac{1}{2}l_p\,s_\varphi\,c_\theta \end{cases},$$

$$S_2:\begin{cases} X_{S2}=X_E-\frac{\sqrt{3}}{3}l_p\,c_\psi\,c_\theta \\ Y_{S2}=Y_E-\frac{\sqrt{3}}{3}l_p\,s_\psi\,c_\theta \\ Z_{S2}=Z_E+\frac{\sqrt{3}}{3}l_p\,s_\theta \end{cases}, \tag{1}$$

$$S_3:\begin{cases} X_{S3}=X_E+\frac{\sqrt{3}}{6}l_p\,c_\psi\,c_\theta+\frac{1}{2}l_p\,c_\psi\,s_\theta\,s_\varphi-\frac{1}{2}l_p\,s_\psi\,c_\theta \\ Y_{S3}=Y_E+\frac{\sqrt{3}}{6}l_p\,s_\psi\,c_\theta+\frac{1}{2}l_p\,s_\psi\,s_\theta\,s_\varphi+\frac{1}{2}l_p\,c_\psi\,c_\theta \\ Z_{S3}=Z_E-\frac{\sqrt{3}}{6}l_p\,s_\theta+\frac{1}{2}l_p\,s_\varphi\,c_\theta \end{cases}.$$

Using the coordinates of the spherical joints and the geometrical parameters of the structure the inverse geometric model of the robotic system which characterizes the vector of the active prismatic joints $Q=[q_i,\ i=1..6]^{\mathrm{T}}$ with respect to the independent coordinates of the end-effector, namely the vector $X=[X_E,Y_E,Z_E,\psi,\theta,\varphi]^{\mathrm{T}}$ is calculated [26]:

$$q_1=\frac{1}{2l_1}\left(l_1+l_2\right)\left(q_2-q_1\right)+Z_{S1}, \tag{2}$$

$$q_2 = \frac{1}{l_1 + l_2}\Big[\left(l_1 + l_2\right)q_1 +$$
$$+2l_1\sqrt{-X_{S1}^2 - Y_{S1}^2 - l_0^2 + \left(l_1 + l_2\right)^2 + 2l_0\sqrt{X_{S1}^2 + Y_{S1}^2}}\Big],$$

$$q_3 = \frac{1}{2l_1}\left(l_1 + l_2\right)\left(q_4 - q_3\right) + Y_{S2},$$

$$q_4 = \frac{1}{l_1 + l_2}\Big[\left(l_1 + l_2\right)q_3 -$$
$$-2l_1\sqrt{-X_{S2}^2 - l_0^2 + \left(l_1 + l_2\right)^2 - \left(L_V - Z_{S2}\right)^2 + 2l_0\sqrt{\left(L_V - Z_{S2}\right)^2 + X_{S2}^2}}\Big]$$

$$q_5 = \frac{1}{2l_1}\left(l_1 + l_2\right)\left(q_6 - q_5\right) + Z_{S3},$$

$$q_6 = \frac{1}{l_1 + l_2}\Big[\left(l_1 + l_2\right)q_5 +$$
$$+2l_1\sqrt{-X_{S3}^2 - l_0^2 + \left(l_1 + l_2\right)^2 - \left(L_H - Y_{S3}\right)^2 + 2l_0\sqrt{\left(L_H - Y_{S3}\right)^2 + X_{S3}^2}}\Big]$$

The kinematic model is used to generate a set of medically relevant motions that are integrated and visualized in the virtual environment.

3. 2. SOFTWARE APPLICATION DEVELOPMENT

The development of the application, composed of two modules was created in Unity. Unity is a game engine platform, which provides a versatile suite of tools for developers and engineers, offering favorable support for AR applications through MRTK (Mixed reality toolkit) package.

The application has two modules: the simulation module, where the robot can be visualized executing the medical protocol, and the interactive module where the user can interact with the robot controlling its motion. The interface was created using MRTK tool.

The simulation module was created based on the mathematical model using different functionalities such as “Joint Configurable” and #C scripts. Configurable Joint is a powerful functionality in Unity which offers the possibility to create kinematic chains capable of behaving as real mechanisms. This functionality allows setting movement constraints between robot components, movement limitations for each individual component and movement based on “artificial drivers”, reproducing in this way a viable physics environment. Based on the child-parent hierarchy from Unity and Configurable Joint component, the kinematic chains were created considering the kinematic scheme of the robot – Fig. 5.

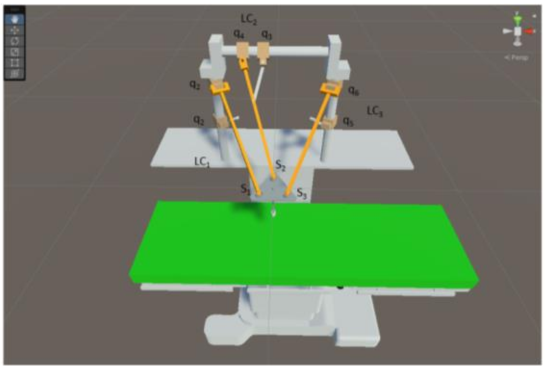

Fig. 5 – The integration of the parallel robot CAD model in Unity.

The schematic representation of the developing for simulation module is presented in Fig. 6.

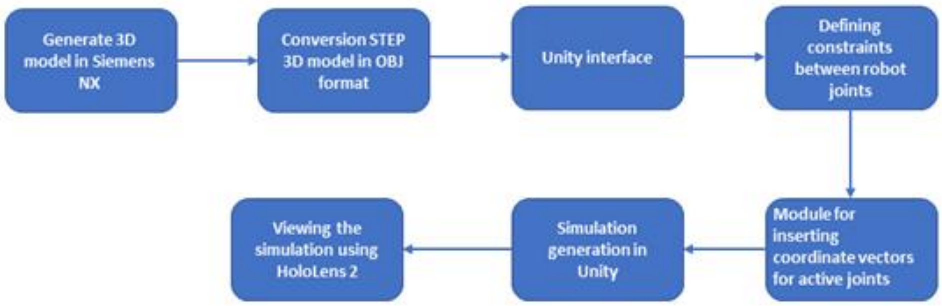

Fig. 6 – Schematic representation of the developing for simulation module.

The CAD model from NX Siemens is exported in STEP format and converted in FBX format (format supported by Unity). This model is imported in Unity 3D where are defined the relation between the joints and the constraints as same as the scripts for the motion.

The interactive module offers the possibility to move or re-scale the entire robot, and the possibility to interact with every joint or with the mobile platform. This module is very useful in the development phase where the engineers have the possibility to visualize the robot in different configurations and sizes, have the opportunity to actuate the system in multiple configurations for a better integration in the operating room, and can interact with the robot to exemplify the right movements. A schematic representation of the developing for the interactive module can be seen in Fig. 7.

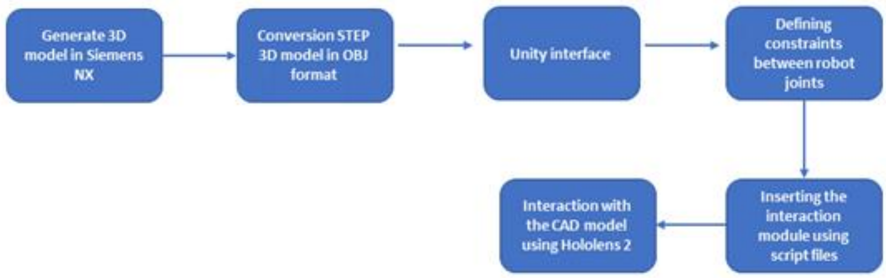

Fig. 7 – Schematic representation of the developing for interactive module.

4. TRAJECTORY GENERATION USING THE KINEMATIC MODEL OF THE ROBOT

For the **simulation module,** a medically relevant motion was generated to enable doctors to visualize the behavior of the digital model of the robot in the operating room. The motions are generated using the mathematical model presented in Section 2, also enabling the validation of the digital model of the robot. At this stage, a single instrument was used to keep the focus on the parallel mechanism. Figure 8 illustrates a sequence of three motions, as follows:

1) – the robot positioning from its current location to the insertion point of the instrument inside the patient body;

2) – the insertion of the instrument, following a vertical trajectory inside the patient body;

3) – the motion of the instrument inside the body, around the insertion point (RCM), kept fixed along the longitudinal axis of the instrument.

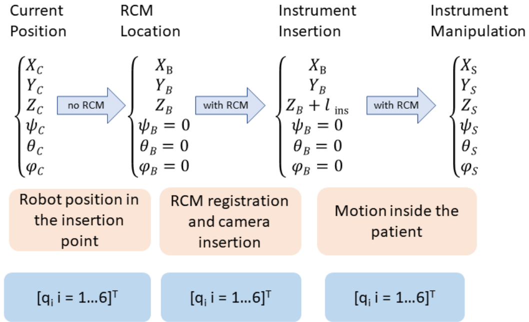

Fig. 8 – The tasks of robotic-assisted SILS procedure.

The robotic system motion begins from the current position of the instrument tip, defined by a set of six coordinates: $X_C, Y_C, Z_C, \psi_C, \theta_C, \varphi_C$, heading toward the insertion point in the patient body, defined by the point $B(X_B, Y_B, Z_B)$. In preparation for the next motion, the insertion inside the body, the instrument will be positioned vertically, meaning that the three orientation angles will be all equal to zero: $\psi_B = 0, \theta_B = 0, \varphi_B = 0$. When the robot achieves the target position, the RCM point is registered, and it will be used from now on as a fixed point along the longitudinal axis of the instrument. The next step is the insertion of the instrument inside the patient body, achieved mathematically by moving the instrument along the Z axis with given length: l_{ins}. The last step is the motion of the instrument inside the body to a new position $S = \left[X_S, Y_S, Z_S, \psi_S, \theta_S, \varphi_S\right]^{\mathrm{T}}$. The mathematical calculations are performed using the kinematic model implemented in MATLAB resulting in a set of motions at the level of the active joints. This data will be transferred in Unity in each active joint as a set of time-based displacements.

For the simulations, the robot parameters were extracted from the digital model, having the following values:

$$\begin{aligned} &l_o = 50 \text{ mm},\ l_1 = 182 \text{ mm},\ l_2 = 392 \text{ mm},\\ &l_p = 135 \text{ mm},\ L_B = 612 \text{ mm},\ L_V = 657 \text{ mm}. \end{aligned} \tag{3}$$

For the sequence of three motions, defined above, the following independent coordinates at the level of the instrument tip were used (all linear dimensions in millimeters (mm) and angular dimensions in degrees (°):

Table 2
Independent coordinates

Starting point	**Starting point**	**Starting point**
$C: \begin{cases} X_C = 407.9 & \psi_C = 10 \\ Y_C = 306 & \theta_C = 15 \\ Z_C = 211.4 & \varphi_C = 10 \end{cases}$	$B: \begin{cases} X_B = 380 & \psi_B = 0 \\ Y_B = 280 & \theta_B = 0 \\ Z_B = 185 & \varphi_B = 0 \end{cases}$	$I: \begin{cases} X_I = 380 & \psi_I = 0 \\ Y_I = 280 & \theta_I = 0 \\ Z_I = 145 & \varphi_I = 0 \end{cases}$
Target point	**Target point**	**Target point**
$B: \begin{cases} X_B = 380 & \psi_B = 0 \\ Y_B = 280 & \theta_B = 0 \\ Z_B = 185 & \varphi_B = 0 \end{cases}$	$I: \begin{cases} X_I = 380 & \psi_I = 0 \\ Y_I = 280 & \theta_I = 0 \\ Z_I = 145 & \varphi_I = 0 \end{cases}$	$T: \begin{cases} X_T = 400 & \psi_C = 15 \\ Y_T = 310 & \theta_C = 20 \\ Z_T = 135 & \varphi_C = 10 \end{cases}$

The calculated data for the active joints were used as inputs in the Unity model and the motion of the instrument tip was recorded and compared to the MATLAB data. Figures 9 and 10 illustrate the results of the simulation showing the displacements, speeds and accelerations for the active joints (used as input data) and the resulting ones for the instrument tip (each motion stage was also marked on the figure). In Fig. 10 it can be seen that there are no differences between the MATLAB calculated data and the Unity measured one, which considering that the model is mechanically perfect (no friction and no plays) validates the mathematical model and the robot integration in Unity. As a result, this model can then be transferred to the **interaction mode** where the user can interact with the instrument tip and by moving it, the robot will move accordingly.

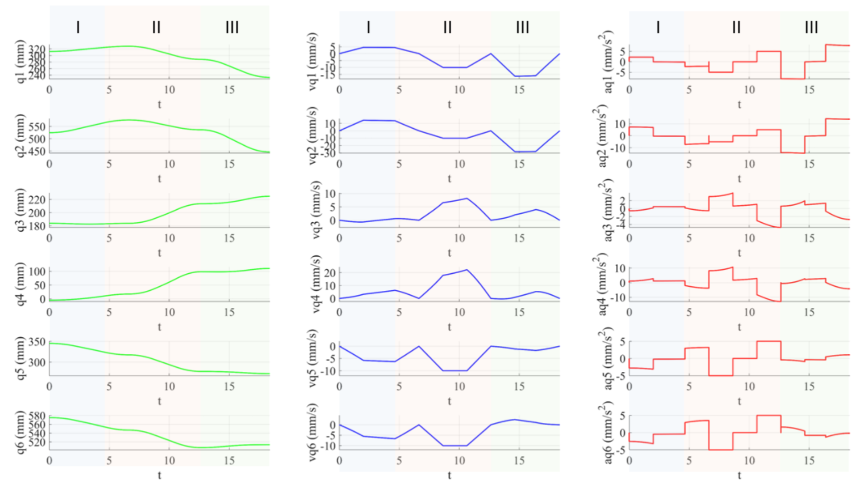

Fig. 9 – Time history diagram for the active joints of the parallel robot (displacement, speed, acceleration).

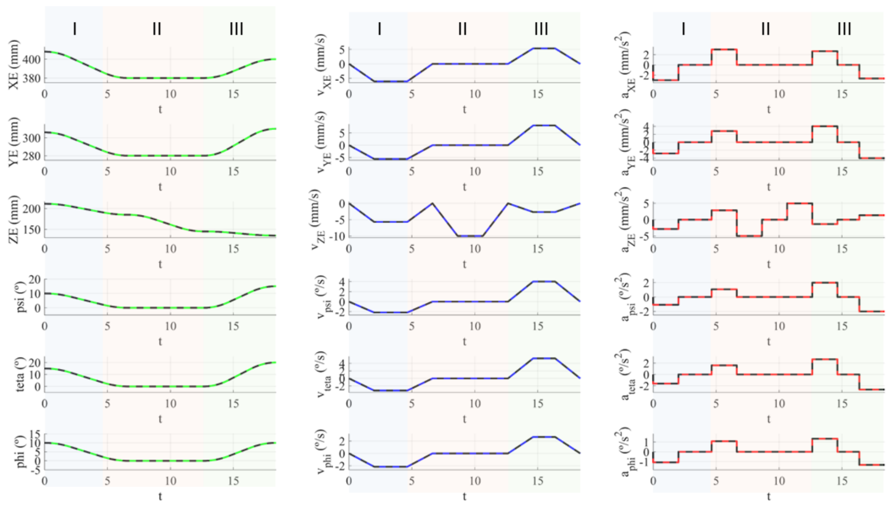

Fig. 10 – Time history diagram for the motion sequence defined for the parallel robot mobile platform; green, blue, red lines (MATLAB computed data); black dashed lines (Unity data).

In the next figures some screen captures from the AR environment are illustrated from both modules. In Fig. 11, in the **interaction mode** it can be seen how the “virtual hand” of the user is interacting with the robot platform.

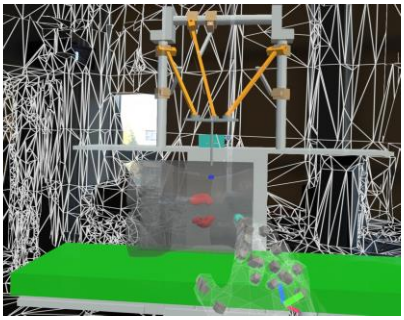

Fig. 11 – a) Interactive module – before interaction.

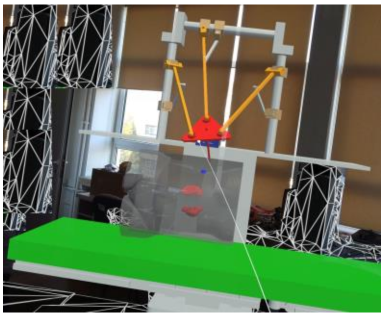

Fig. 11 – b) Interactive module – real time interaction.

Figure 12 presents the simulation module of the robotic system which embeds the kinematic equations.

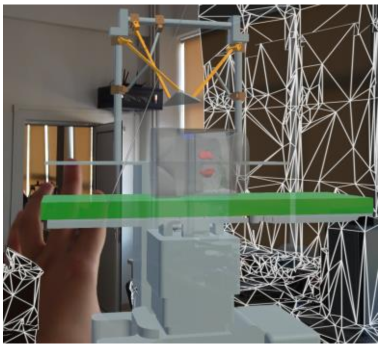

Fig. 12 – a) Home position.

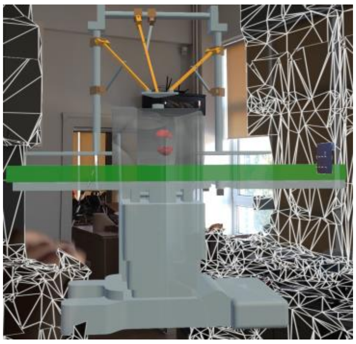

Fig. 12 – b) Mobile platform at trocar (RCM point).

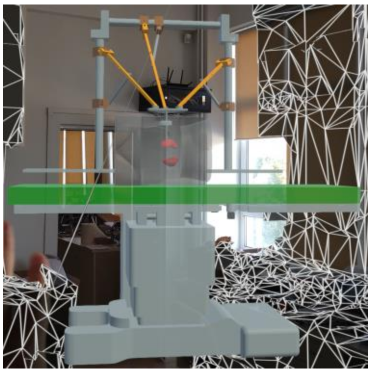

Fig. 12 – c) Instrument insertion.

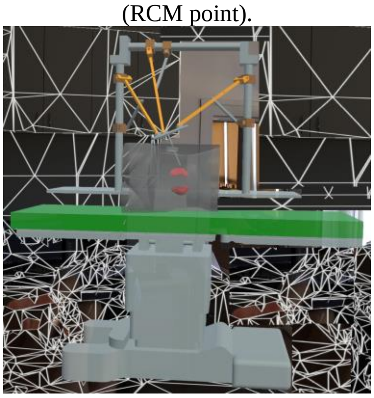

Fig. 12 – d) Mobile platform orientation.

5. CONCLUSION

This paper presented a new approach of using Hololens 2 in robotic assisted SILS, developing an application with two modules, interactive module and simulation module, in order to create a simulator for a 6-DOF innovative parallel robot used in single incision laparoscopic surgery. The simulation module offers the possibility to observe and analyze the simulation of the robot executing the medical task based on the mathematical model, while the interactive module offers the opportunity to interact with the mobile platform and the active joints.

Further work is oriented to integrate the AR simulator into the robotic system control.

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