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Design, simulation and first test of an automatic suturing device coupled to a robot

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Abstract

Objective: Robotic assistants are becoming a very helpful tool for surgeons. As for the suturing procedure, several commercial devices assist the physician in suturing. However, such devices have not yet been coupled to a robot assistant in order to perform sutures fully automatically. This could contribute to a procedure that is often routinely performed but requires time and dexterity.

Materials and methods: This article presents the adaptation of a commercial manual suture gripper, the Medtronic Endo Stitch, to a Universal Robots UR3 robot. The gripper was modeled in SolidWorks, as well as a motorized coupling device, which were simulated in CoppeliaSim. Once its proper functioning was verified, the device was fabricated in a 3D printer and coupled to a UR3 robot, then its operation was tested in the tracking of a suture trajectory with displacement.

Results: The trajectories planned in Matlab are sent to the UR3 robot via ROS. It was possible to verify the good performance of the suture movement with displacement, carried out by the printed device and by the Endo Stitich gripper. The opening and closing of the gripper was also obtained under the action of the motors included in the device.

Conclusions: The motorized device together with the Endo Stitch gripper, coupled to the UR3 robot, is capable of following the trajectories required for automatic suturing. Future work will test suturing with thread on a test phantom in order to measure its true potential for automatic suturing.

Keywords: Automatic suture, Colaborative robots, Virtual environment, Endo Stitch device.

Diseño, simulación y primera prueba de un dispositivo de sutura automática acoplado a un robot

Resumen:

Objetivo: Los asistentes robóticos se están convirtiendo en una herramienta de gran ayuda para los cirujanos. En cuanto al procedimiento de sutura, aunque existen varios dispositivos comerciales que le ayudan al médico a realizarla, todavía no se han acoplado dichos dispositivos a un robot asistente con el fin de realizar suturas de manera completamente automática. De esta manera se contribuiría con un procedimiento que muchas veces es rutinario pero que requiere tiempo y destreza.

Materiales y métodos: Este artículo presenta la adecuación de una pinza manual de sutura comercial, la Endo Stitch de Medtronic, a un robot UR3 de Universal Robots. La pinza fue modelada en SolidWorks, así como un dispositivo de acople motorizado, los cuales fueron simulados en CoppeliaSim. Una vez verificado su buen funcionamiento, el dispositivo fue fabricado en una impresora 3D y acoplado a un robot UR3, probándose entonces su funcionamiento en el seguimiento de una trayectoria de sutura con desplazamiento.

Resultados: Las trayectorias planificadas en Matlab son enviadas al robot UR3 vía ROS. Se pudo comprobar el buen desempeño del movimiento de sutura con desplazamiento, efectuado por el dispositivo impreso y por la pinza Endo Stitich. Igualmente se obtuvo la apertura y cerrado de la pinza bajo el accionar de los motores incluidos en el dispositivo.

Conclusiones: El dispositivo motorizado junto con la pinza Endo Stitch, y acoplado al robot UR3, es capaz de seguir las trayectorias necesarias para la realización de una sutura automática. Trabajos futuros realizarán pruebas de sutura con hilo sobre un phantom de prueba con el fin de medir su verdadero potencial para realizar suturas de manera automática.

Palabras clave: Sutura automática, Robots colaborativos, Ambiente virtual, Pinza Endo Stitch.

1. Introduction

The accelerated growth in the use of robotic-assisted surgery in recent years is due to its advantages over traditional surgical methods. (Nuzzi & Brusasco, 2018). Robotic surgery allows solving many of the limitations of laparoscopic surgery, such as increased physiological tremors at the tip of the instruments, collisions and limited movements due to the linearity of the laparoscopic gripper, and two-dimensional vision due to the loss of depth perception. In addition, in surgeries with a long operating time where delicate sutures are required, surgeons are fatigued, which is a possible source of adverse events, compromising safety and generating complications for the patient (Díez del Val et al., 2019).

The application of robots in surgery achieves a precision that is not possible to obtain with unassisted manual techniques. It also increases the surgeon's dexterity in confined body spaces and maneuverability without direct visualization, allowing access to specialized procedures in teleoperated environments (Nuzzi & Brusasco, 2018).

The surgical procedures that can be performed by these robots are dissection, tissue manipulation and suturing. This last procedure is one of the most complicated, demanding more time in minimally invasive surgery (MIS), with a higher degree of difficulty if the surgeon's skills are diminished due to fatigue or if visual feedback is limited. Although robotic surgery has solved some of the aforementioned problems, suturing with the aid of surgical robotic systems continues to have difficulties and its repetitive process makes this procedure of great interest for automation (Pedram et al., 2017), (Bauzano et al., 2013). Performing it by means of an automatic and robotic procedure could reduce operating time and improve precision without having problems with surgeon fatigue, in addition to being able to perform remote sutures by means of remote operation, thus solving the complications that currently exist due to the latency that hinders control in master-slave mode (D'Auria & Persia, 2017).

Because suturing is a significant stage of surgery that demands time and skill in the surgeon, some automated suturing devices have been developed in order to facilitate intracorporeal suturing to be a dynamic, complete and autonomous process (Huhn, 2016). This also allows procedures treated in open surgery to be possible via laparoscopy (Cho et al., 2016), (Kam et al., 2021), (Hideki et al., 2015).

Some of the most important manual devices for suturing are: Jhonson & Jhonson's Proxisure, which works with curved needles inside single-use cartridges, where the gripper tip moves with a 45° articulation in both directions and has a 360° rotation; the EndoSew, which has three basic parts, the motor, the gearing and the needle unit (Brehmer et al., 2008); OverStich Apollo, which is a system that attaches to a dual-channel endoscope for suturing with a curved needle (Galvao-Neto et al., 2016); Flexible endoscopic robotic suturing system, a system containing a needle controller and a clamp, both flexible, robotic and with 5 degrees of freedom (Lin et al., 2020); FlexDex surgical system, with a 3-axis handle that carries the surgeon's hand, wrist and arm movements to the end effector containing the needle, providing 7 degrees of freedom (García et al., 2021); Endo360, 12 mm laparoscopic instrument, with curved needle and rotation and angulation movements to allow continuous suturing (Leeds et al., 2017), (Guevara, 2019); Endo Stitch, where the end effector has opposing jaws with holes where a double tapered suture needle is positioned, with a rotating lever in charge of transferring the suture needle from one jaw to the other (Huhn, 2016).

The aforementioned devices, some of which have been on the market for several years, are all manual, i.e., they operate under the direct action of the surgeon. This paper shows the design, simulation and test of a first prototype of a suture gripper coupled to a robotic assistant, as a first step towards an automatic suture performed by robots.

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2. Materials and methods

2.1. Choice of device to be motorized

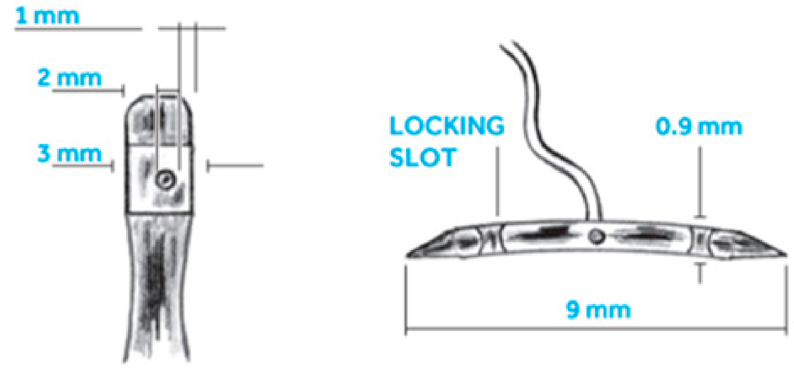
The first step of this project was based on a detailed study of the manual suturing devices present on the market or the result of promising research in the area. The initial objective was to choose, under certain criteria, the best device to be automated and coupled to a robot arm. After reviewing the state of the art and making a comparison of the existing devices in terms of the characteristics shown in Table 1, it is found that the Endo Stitch tool (Melzer et al., 1994; Medtronic, 2022) is one of the most used and most complete tools to perform sutures in open or laparoscopic operations, since it allows intracorporeal knots, and its buttons and movement handles are easily accessible (Nguyen et al., 2000).

Table 1. *Comparison Of Sutura Devices*

Device	Needle	Wrist	360° rotation	Continuous suture	Use in humans	Ease in knots
Proxisure	Curve	Yes	Yes	Yes	No	No
Overstitch	Curve	No	No	Yes	Yes	Yes
Endo360	Curve	Yes	Yes	Yes	No	No
Endo Stitch	T	No	No	Yes	Yes	Yes

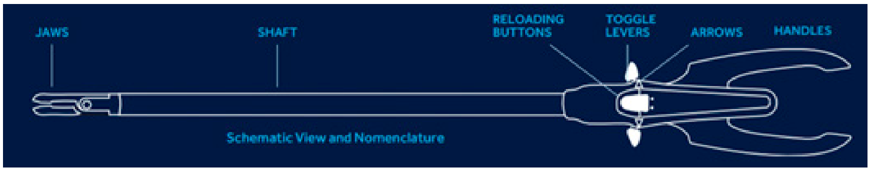
The Endo Stitch facilitates endoscopic suturing and intracorporeal knot tying, is used in most laparoscopic procedures requiring suturing, contains a needle integrated with the suture that comes in a cartridge ready for loading (Medtronic, 2022). The axis of the device has a diameter of 10 mm and a length of 36 cm, which facilitates access to the tissue. The jaws are 4 mm wide and the needle is closer to the edge of the jaw allowing the jaw to have more access to the tissue. The needle is double, 9 mm long (see Figure 1) and has sharp points to facilitate tissue penetration.

Figure 1. Endo Stitch jaw and needle. Source: Medtronic,2022.



On the handle are two levers, two black discharge buttons (one on the front and one on the back) as shown in Figure 2, and two grips. The needle is transferred from one jaw to the other by fully squeezing the handles and pulling the lever forward or backward.

Figure 2. Parts of the Endo Stitch, Medtronic, 2022.



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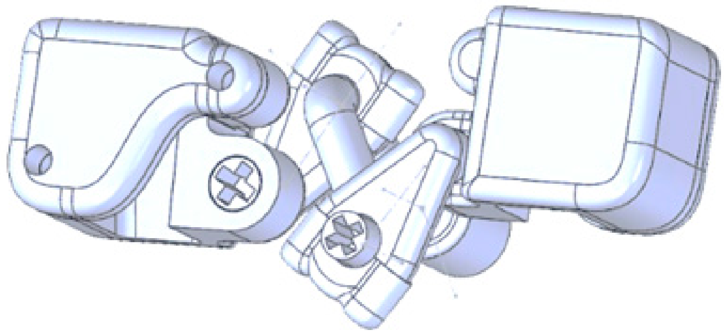
Modeling of the new device

With the tool selected and reviewing the process to perform a suture, it was decided that the movements of the instrument to be automated are those of loading and unloading the needle, transferring the needle from one jaw to another, and closing and opening the jaws. A modeling of the Endo Stitch device was then performed in SolidWorks software, which is shown in Figure 3.

Figure 3. *Modeling of the Endo Stitch device. Source: own.*

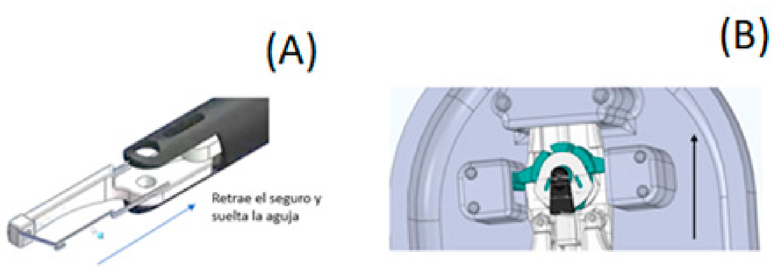
Servomotors were selected as motion actuators in order to protect the maximum ranges of opening and closing of the gripper, and thus meet the characteristics of size, weight and torque to move both buttons and handles of the Endo Stitch. For the opening and closing movement of the gripper, a design was made by attaching each of the Endo Stitch handles to a connecting rod that is linked to the crankshaft, which with the engine turns allows the two handles to open or close according to the desired movement. Figure 4 shows the parts of this mechanism and its assembly with the Endo Stitch.

Figure 4. *Mechanism for the opening and closing movement of the gripper. Source: own*



The needle transfer movements are performed by a servomotor that moves the needle transfer lever. This motor causes the latch to retract and release the needle from jaw 1 and in turn releases the latch on jaw 2, so that the needle can be secured, and in this way the needle passes from one jaw to the other. Figure 5(a) shows the latch in the jaw and Figure 5(b) shows the lever mechanism with the latch position.

Figure 5. *Mechanism for the needle transfer: (A) Needle lock (B) Mechanism for the needle transfer movement. Source: own*



For the coupling of the device to the robot, the housing is designed taking into account the measurements of the end flange, given by the manufacturer in the user manual, as shown in Figure 6.

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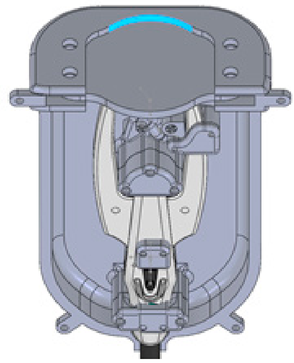
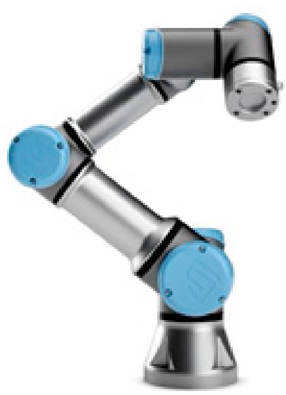
Figure 6. *Robot coupling base. Source: own.*



UR3 robot

In robotic surgery, several works have been performed with collaborative robots in different medical specialties (Beuss et al., 2021), (Muñoz, 2020), (Vivas & Sabater, 2021), (Chen et al., 2022). Many of the current jobs are performed using the Universal Robots UR robot, either the UR3 or UR5. This work uses the UR3 robot, a light, fast, easy to program, small robot, with a weight of 11kg, payload of 3kg, 6 degrees of freedom, 360° rotation at each joint and infinite rotation at the end of each joint (Universal Robots UR3e, 2022), (Figure 7).

Figure 7. *UR3 Robot. Source: Universal Robots.*

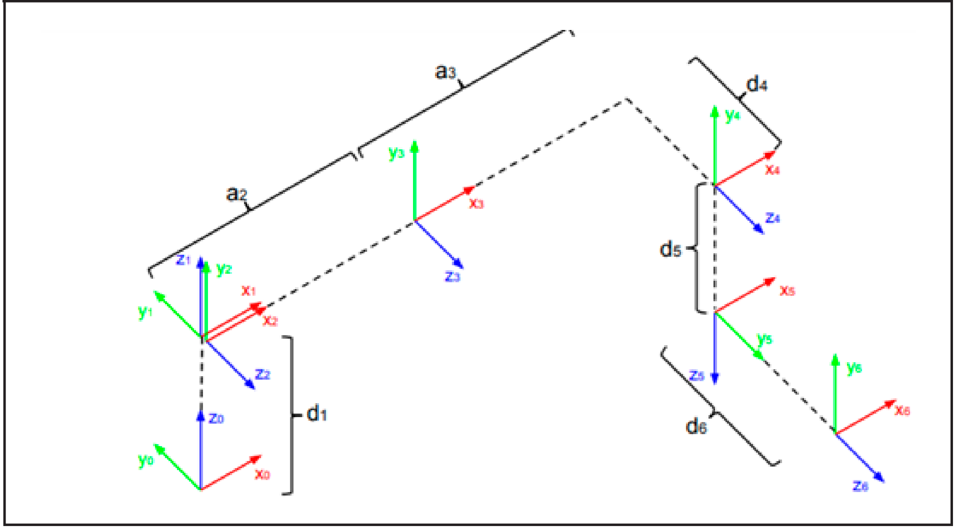


To perform the movements in the UR3 robot there are different ways to generate them, each one with advantages and disadvantages. Some of them are (Gonzalez, 2018):

- ***Polyscope***: The graphical interface, developed by Universal Robots, is operated through the touch screen included with the robot, based on the Debian Linux operating system.
- ***Script***: URscript is a proprietary programming language used to control the robot. It works similarly to other programming languages.
- ***Robot Operating System (ROS):*** This system allows that a code (program) can be loaded in different robots, it also allows communication between different programs in order to share data and in this particular case, to operate the UR3 robot from another source or program (ROS. Robot Operating System, 2022).

To perform the robot movements, the simulation worked with the inverse and direct kinematics of the UR robot developed by Rasmus Andersen according to the coordinate axes of the UR robot (Andersen, 2018) (*Figure 8.*), and also taking into account Paez's comments (Páez et al., 2021). Some of this kinematics was used in the initial simulations of the robot.

Figure 8. *UR coordinate axes. Source: (Andersen, 2018).*



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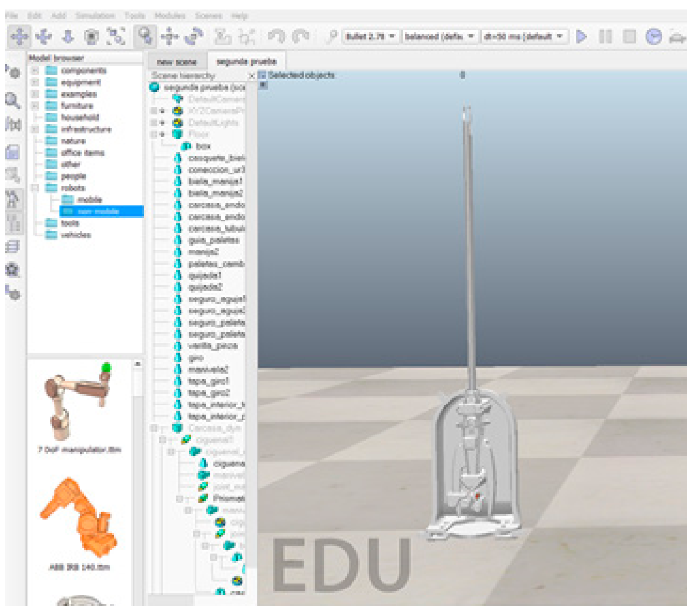
The robot movements are performed using Matlab, Simulink and CoppeliaSim, using the Paez algorithm as a basis (Páez et al., 2021). That is, the trajectories are generated and tested in Matlab, then entered into CoppeliaSim, where the robot with the suturing device is located, in order to obtain the movements required for a suture. Later the movements generated by Matlab were sent directly to the real robot via ROS, where the kinematics are included in the Industrial Robots package.

Simulation in CoppeliaSim

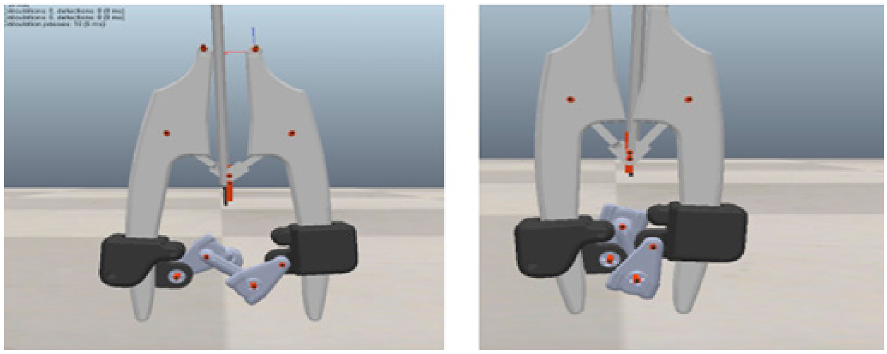
The open source software CoppeliaSim EDU was used to simulate the movements of the device. The first step was to design in a design program (SolidWorks) the device and the Endo Stich gripper, place them in STL (Standard Triangle Language) format and then import them from the simulator using the import -- mesh tool (Figure 9).

Figure 9. *Device imported into CoppeliaSim. Source: own*



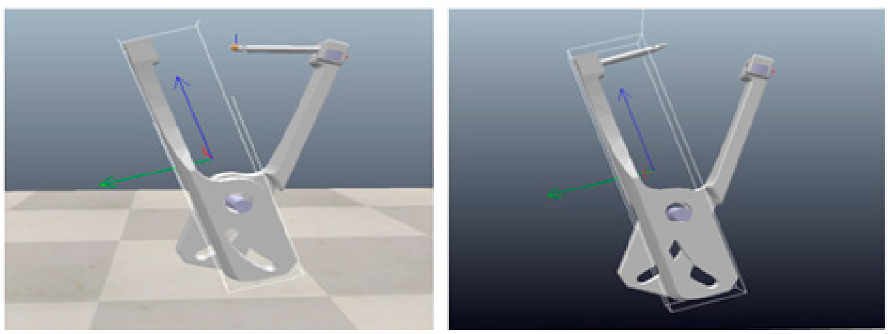
To simulate the movements of the gripper, the kinematic and dynamic configurations of the device were made in order to be able to appreciate the closing and opening movements of the gripper according to the designed mechanisms, as shown in Figure 10.

***Figure 10**.Simulation of opening and closing the gripper of the device. Source: own.*



The transfer of the needle from one jaw to the other was also simulated, as shown in Figure 11.

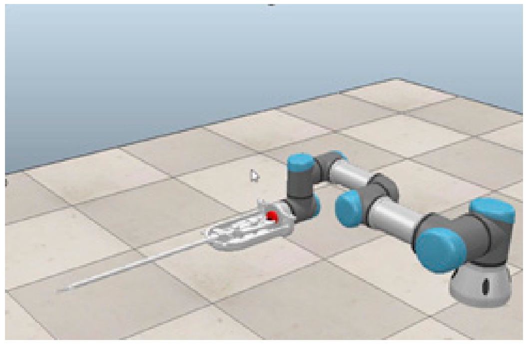
***Figure 11**. Simulation of needle transfer. Source: own.*



The CoppeliaSim software has its own library of robots and within this library is the UR3 robot, which is inserted into the environment and is coupled with the model of our device (see Figure 12). First the UR3 is brought to an initial position, the distance between points of the suture and the number of points to be performed are defined. With these values a matrix of points is generated by means of a

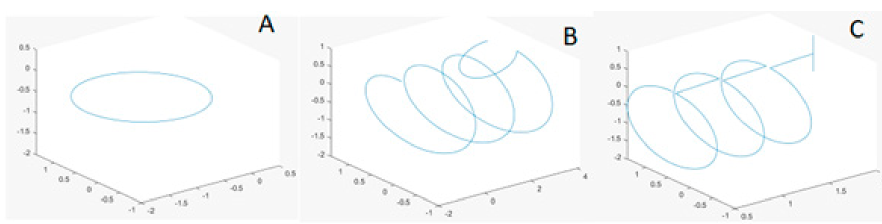
Matlab code, points that will later be placed in the Lua language of CoppeliaSim in order to move the robot in simulation.

Figure 12. *Device coupled to the UR3. Source: own.*



With this procedure, tests were performed with different trajectories to check the movements of the forceps. The trajectories executed were: ring trajectory, suture trajectory, which is the movement performed by the surgeon to execute a needle suture, and the suture trajectory with displacement, which is the suture movement performed by the surgeon with the Endo Stitch forceps. These movements are shown in Figure 13.

Figure 13. *Programmed trajectories: (A) ring, (B) suture, (C) suture with displacement. Source: own.*



The movements performed in simulation by the device in CoppeliaSim are shown below: the trajectory performed by the robot (yellow color) to be placed in initial position and their respective graphs of its movement in the three axes (Figure 14). And Figure

15 shows the tip of the gripper performing a suture trajectory with displacement and the graph of positions in the three axes 15.

Figure 14. *Simulation of a trajectory from its initial position in CoppeliaSim. Source: own.*

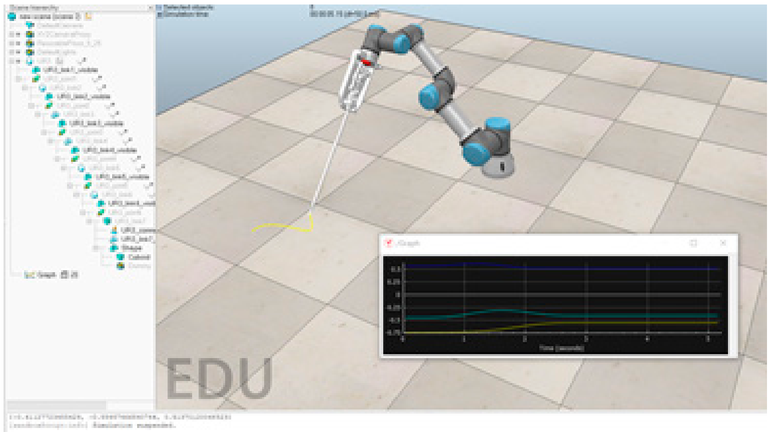
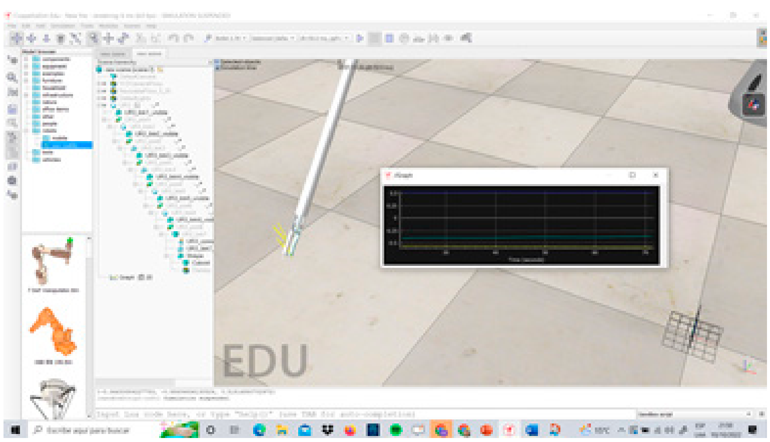


Figure 15. *Simulation of the robot movement for the suture trajectory. Source: own.*



Fabrication and initial test of the device

Finally, a first prototype of the device that holds the Endo Stitch gripper was fabricated using a 3D printer. Two motors were used: a SG90 of 1.6 kg/cm (0.15 Nm) for the needle transfer and a MG995 of 8.5kg/cm (0.83 Nm) for the Endo Stitch closure. The motorized device was attached to the actual UR3 robot. The suture movement commands were generated from Matlab and sent to the UR3 robot via ROS. Figure 16 shows in detail the device together with the Endo Stitch forceps, as well as its coupling to the UR3 robot.

Figure 16. *Device with the Endo Stitch gripper attached to the UR3 robot. Source: own.*

The first tests allowed the robot, together with the designed device, to follow a suture trajectory with displacement, as performed in the simulation phase. The maximum error obtained in the trajectory tracking was 11 milli-radians, a value between the articular setpoint sent to the ROS channel and the data read from the same channel once the trajectory was completed. The desired setpoint was sent from Matlab while the data were read from a terminal in ROS. In future work, tests will be performed with thread and needle on a gel phantom in order to verify the potential of the system as a fully automatic suture generator.

3. Conclusions

This article showed the design of an automatic suturing tool attached to a collaborative robot. A commercial suturing device was chosen to be modified so that it could operate automatically and be attached to a Universal Robots UR3 six-degree-of-freedom robot.

The new device attached to the UR3 robot was introduced and simulated in CoppeliaSim software, where from different suture trajectories programmed in Matlab and translated into CoppeliaSim's Lua language, it was possible to observe the behavior of the robot together with the device, simulating automatic suturing movements. The designed device was also tested to open and close, allowing the needle to pass from one jaw to the other, in order to perform a suture. Finally, the device was built using a 3D printer, two motors and the Endo Stitch gripper were added, and its operation was tested by performing a suture trajectory with displacement. The error during this trajectory is very small (11 mrads), being able to test the opening and closing of the Endo Stitch under the action of the two motors.

Future work will perform a first suture test on a surgical test phantom and then experiment the system on animal tissue.

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