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LETTER

System for assistance in ultrasound-guided percutaneous hepatic interventions using augmented reality: First steps

Lucía Salazar Carrasco[1] | Ignacio Sánchez-Varo[1] | Daniel Caballero Jorna[1] | Amaia Iribar-Zabala[2] | Álvaro Bertelsen-Simonetti[2] | Juan A. Sánchez-Margallo[1] | Francisco M. Sánchez-Margallo[3]

[1]Bioengineering and Health Technologies Unit, Jesús Usón Minimally Invasive Surgery Centre, Cáceres, Spain

[2]Digital Health & Biomedical Technologies, Vicomtech, Donostia/San Sebastián, Spain

[3]Scientific Direction, Jesús Usón Minimally Invasive Surgery Centre, Cáceres, Spain

Correspondence
Juan A. Sánchez-Margallo, Bioengineering and Health Technologies Unit, Jesús Usón Minimally Invasive Surgery Centre, Cáceres 10071, Spain.
Email: jasanchez@ccmijesususon.com

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Abstract
This study aims to develop a system based on mixed reality imaging for assistance in percutaneous ultrasound-guided liver interventions. A liver phantom, an ultrasound scanner with an abdominal probe, an electromagnetic tracking system for localization of the ultrasound probe, and the percutaneous needle were used to develop the system. A gelatin liver phantom was fabricated, including a set of lesions (with agarose, glycerol, and sephadex) and artificial blood vessels 3D printed with thermoplastic polyurethane (TPU) elastic fibres. Intraoperative ultrasound images from a BK5000 ultrasound scanner were acquired using a video capture system and transmitted to 3D Slicer. The NDI Aurora electromagnetic tracking system, coupled to the ultrasound probe and intracorporeal needle, was used for real-time trajectory tracking, providing us with spatial localization information. These images are then sent to the augmented reality HoloLens device as the primary visualization system. This work lays the groundwork for the development of a more comprehensive system to assist ultrasound-guided percutaneous liver interventions in order to improve the accuracy and safety of these procedures. The use of mixed reality imaging technology allows a better integration of image-guided surgery systems, such as the one presented in this work, in real clinical environments, and closer to the patient.

1 | INTRODUCTION

Minimally invasive surgery procedures have exponentially grown in the last decades as alternatives to open surgery [1]. These include percutaneous interventions, which are commonly used for local diagnosis and treatment of deep tissue structures, such as biopsy or radiofrequency ablation. This approach has several advantages over open surgery, such as less tissue trauma, diminished postoperative pain, shorter recovery time, and reduced scarring [2].

1.1 | Background

Several locoregional treatment techniques are becoming increasingly accepted as treatment methods for malignant tumours of some organs and soft tissues [3]. In general, percutaneous surgery is recommended in cases where the tumoural lesion is in a difficult-to reach zone or highly vascularized area, such as in the case of the liver.

Global attention has increased towards enhancing clinical ethics and adopting simulation stages in the last years [4], which in return facilitates an adequate training experience for clinical trainees towards improving and promoting medical practices [5]. Nowadays, the use of phantoms as simulators has enhanced the learning experience for novice surgeons [6].

The phantoms consist of materials that mimic human tissues and organs [7]. These phantoms are necessary for the training of novice surgeons in percutaneous interventions and diagnostic procedures prior to the application of this knowledge and skills in real clinical practice [8].

Image-based assistance is mandatory for all percutaneous interventions, as there is no visual contact with the internal organs. Therefore, a combination of preoperative and intraoperative images is crucial to plan and execute the intervention [9], with poor guidance being a considerable risk that can lead to incomplete tumour removal [10]. Among existing intraoperative imaging modalities, ultrasounds (US) offer considerable advantages, such as, it provides real-time images, does not generate ionizing radiation, and has lower costs, although it suffers from low penetration depth, limited resolution, and 2D acquisitions. In this way, US is the method of choice for a wide range of percutaneous interventions, although its complexity and technical limitations make its usage a challenging skill [11]. The development of support systems for US-guided percutaneous interventions is expected to facilitate the performance of this type of surgical procedures and consequently, the improvement of the safety and the quality of the surgical procedures and patient health care [12].

Although medical imaging has been a key of medical innovation, its acquisition has made dramatic advances, but its visualization has not evolved at the same pace. Furthermore, different imaging modalities are normally displayed on different devices. This clarifies the needed and highly desirable use of technology capable of fusing medical imaging data together directly over the surgeon's field of view.

Augmented reality (AR) is an innovative technology that offers a solution to this problem, providing the surgeon with an enhanced environment with relevant information. This technology would allow clinicians to avoid having to look away from the patient to consult preoperative and intraoperative patient data on multiple screens [13]. However, there is room for improvement the preoperative and intraoperative patient information with its corresponding real-time anatomy to provide better assistance during surgery. Therefore, the capabilities of AR would be very beneficial for surgical procedures where there is no direct view of the working area.

All these technologies have been applied individually in several studies. However, to the best of our knowledge, few have integrated all these technologies into a US and AR-based assistance system for liver percutaneous surgery. The main novelties of this assistance system focus on the integration of all these planning tools, instrument tracking, and their real-time visualization through AR. Thus, system integration was carried out by using SlicerIGT and Plus Toolkit to enable interaction between 3D Slicer and Mirage and its visualization with the Microsoft HoloLens 2 device. This is novelty compared to previous studies, such as Ungi et al. [14], in which they applied SlicerIGT and Lump Nav for the development of an assistance system for percutaneous interventions. However, the proposed system does not require LumpNav and allows visualization using AR, not enabled by the solution proposed by Ungi et al. [14]. Léger et al. [15] developed a mobile neuronavigation assistance system using AR. They applied the combination of OpenIGTLink and Plus Toolkit for system integration as the proposed solution. However, their assistance system was exclusive for its use in neurosurgery. Beyer et al. [16] developed an assistance system for percutaneous interventions but based on preoperative CT imaging instead of US imaging as the purposed solution.

1.2 | Objectives

Therefore, the aim of this study is to fine-tune all the tools and their integration for the development of an assistance system for US-guided percutaneous surgeries in liver cancer based on AR. With the ultimate goal of facilitating the execution of the procedure, improving its accuracy and safety and, consequently, promoting better surgical outcomes for the patient.

2 | MATERIAL AND METHODS

In the current section, we will describe each of the elements that make up this assistance system and how they have been integrated with each other.

2.1 | Experimental design

Figure 1 shows the experimental design of this work, each of its component elements, and the integration between them. The main idea is to have an augmented visualization system that allows the user to know in real time the location of the intracorporeal needle with respect to the US image plane, facilitating spatial localization with respect to the patient.

2.2 | Liver phantom

In order to test the developments in a controlled environment that simulates the working conditions in a real clinical setting, a liver phantom has been developed. This phantom has echogenic properties for visualization by US and incorporates both lesions and structures that simulate the vascular anatomy of the liver.

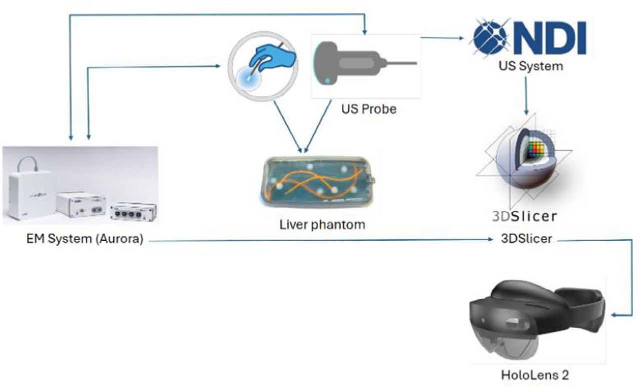

FIGURE 1 Experimental design. A liver phantom made of gelatine is used to perform the ultrasound (US)-guided puncture. Both the US probe and the intracorporeal needle are tracked by an electromagnetic tracking system (Aurora). The US images are processed in 3DSlicer together with the information of the US probe and needle location and streamed to the HoloLens 2 glasses in real time.

Two types of phantoms were designed, one based on kerosene and the other based on gelatin, as the main components to simulate liver parenchyma. The paraffin-based phantom was based on the work of Chamarra et al. [17]. However, we were unsuccessful in visualization by US imaging due to the poor echogenic properties obtained. We consequently proceeded to the development of the second option based on gelatin. A 2000 mL phantom was aimed for this study. Therefore, a recipient of at least 2000 mL capacity (larger is recommended) was required. A box poly lactic acid was 3D printed to create the phantom recipient.

For the creation of the **parenchyma**, porcine gelatin from Scharlab with a concentration of 15% was used.

To simulate the **blood vessels**, they were 3D printed using flexible material (fila flex). The vessels had a diameter of 2 mm and a star-shaped design to facilitate visualization by US imaging.

For the **liver lesions**, 7.5 g of agarose, 30 mL of glycerol, 200 mL of distilled water, and 4 g of sephadex were mixed:

1. Agarose, distilled water, and glycerol were mixed in a conical flask with a stirring magnetic bar.
2. The conical flask was placed on the hot plate magnetic stirrer and heated it up under magnetic steering at the maximum speed of 250 rotations/min. Air bubbles should be avoided.
3. The agarose mixture was boiled for 2 min (approximately).
4. Sephadex was added to the mixture while stirring. Sephadex was distributed in a small quantity of the agarose mixture first. Once it was equally distributed, the mixture was poured over the rest of the agarose mixture.
5. Pigments (if necessary) were added while gently stirring the mixture.
6. The agarose mixture was cooled down to around 40°C while continuously stirring.
7. The agarose mixture was poured into the tumour molds.
8. The tumour moulds were placed in the fridge for at least 0.5 h.
9. The agarose-based tumours were removed from the tumour moulds.

The lesions can be prepared in advance and stored refrigerated.

One the artificial tumours is ready, we procced with the development of the liver phantom.

2.2.1 | First layer

We considered the first layer of the phantom as 1/4 of the total phantom (2000 mL) = 500 mL.

1. Overall, 15% of the mass of the layer (15% of 500 g = 75 g) was dissolved in about 1/4 of the total first layer.
2. (1/4 of 500 mL = 125 mL) of boiling water.
3. When dissolved, room temperature water was added to make up the total first layer (to approximately 500 mL).

FIGURE 2 BK500 ultrasound phantom image transmission.

4. The mixture was cooled down at room temperature for 2 h and later in the refrigerator for 24 h.

2.2.2 | Rest of the phantom

It was considered 3/4 of the total of the phantom (2000 mL) = 1500 mL. We followed the same steps as for the first later, but in this case, the lesions and simulations of the vascular system were added before cooling down the mixture.

2.3 | US imaging acquisition

The BK 5000 US system (BK Medical) with the 6C2 curved array transducer for abdominal scans was used for this study. A gain level of 40, a frequency of 3.5 MHz, and a depth of 10 cm were used for image acquisition (Figure 2).

2.4 | Streaming the US images

In order to capture the US image in real time and in a way compatible with any common US system, the following steps were followed:

1. The video of the US scanner was taken from its DVI output port using a DVI to HDMI cable.
2. The video signal was captured using a USB video capture system (Converty II UNOTEC).
3. A server was implemented in Python using OpenIGTLink to capture the video frames.

FIGURE 3 Aurora electromagnetic tracking system.

4. A 3D Slicer client is created using OpenIGTLink that allows us to insert the US video in the working environment with minimum latency.

As a working environment for the development of the intracorporeal US assistance system, we used 3D Slicer (www.slicer.org), which allows us to visualize, process, segment, record, and analyse medical images, as well as to integrate other elements such as tracking of surgical instruments.

In order to show an image that helps the end user, a mask is made by the Segment Editor tool to hide the unnecessary visual information of the US interface so that only the actual US images are displayed in the navigation system.

2.5 | Tracking system

To track the US probe and the intracorporeal needle, an Aurora electromagnetic (EM) tracking system (Northern Digital Inc.) was used (Figure 3). This system allows us to record in real time the location of both surgical instruments through the use of microsensors and without the need of any visual marker that could be occluded during the surgical practice. The Aurora system's microsensors can be integrated into both rigid and flexible medical instruments, such as US probes, endoscopes, catheters and guide wires, and even the tip of a needle. This unobstructed tracking capability is especially useful for in vivo monitoring of instruments through complex and curved anatomical tracts. This system offers the speed, precision, and accuracy of instrument tracking needed to meet the demands of the most advanced and complex minimally invasive procedures.

To connect the Aurora system to 3D Slicer, PLUS Toolkit was used. Using PLUS Server, an information exchange pipeline is established between Aurora and 3D Slicer by adapting the corresponding configuration file. For this purpose, a client in 3D Slicer is created via OpenIGTLink.

Once the flow of images from the US scanner and the relative locations of the surgical instruments (US probe and intracorporeal needle) are available in 3D Slicer, a system organized by means of transformations and coordinate systems specific to each sensor is created. These transformations arise from the need to calibrate the US image plane with respect to the position of the US probe. To perform this calibration, the 3D Slicer Fiducial Registration Wizard module is used (Figure 4).

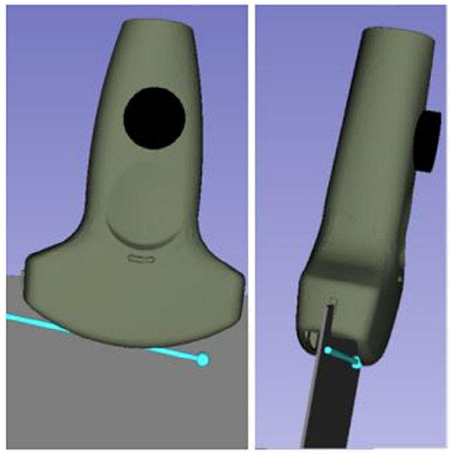

FIGURE 4 Result of the calibration of the ultrasound (US) image plane with respect to the US probe location brought by the electromagnetic (EM) tracking system.

FIGURE 5 HoloLens 2 device for mixed reality applications.

2.6 | Extended reality

The HoloLens 2 mixed reality device (Microsoft) was used to visualize the information of the US-guided intervention assistance system (Figure 5). For this purpose, a real-time streaming connection was established between the interface integrated in the 3D Slicer and the HoloLens glasses. The Mirage (Author: Dominik Konik) holographic remote application was used for this aim with a frame rate of 60 FPS. This application facilitates the creation of virtual remote desktops from HoloLens.

2.7 | System integration

Following the scheme shown in Figure 1, integration was carried out with all the necessary elements to achieve a first version of the AR-based assistance system for US-guided liver punctures.

Once the gelatin-based phantom was created, the convex probe and the BK5000 US scanner were used to obtain the US image showing the structures of the simulated blood vessels and tumours. This US image is registered with respect to the position of the US probe and visualized together with the intracorporeal needle in the 3D Slicer working environment by using SlicerIGT, IGTOpenLink, and Plus Toolkit. This virtual guidance interface was visualized in mixed reality with the HoloLens device, which establishes a connection between 3DSlicer-HoloLens by means of a QR code. All this allows the clinician to know in real time, and on the patient's real image, the position of the intracorporeal needle with respect to the US image plane, which would not be possible with the naked eye in a traditional intervention.

Six participants with varying experience in US imaging were asked to participate in an initial subjective validation of the developed assist system. All of them had previous experience in US imaging.

3 | RESULTS AND DISCUSSION

Image-based assistance systems play a crucial role in US-guided percutaneous interventions. These procedures involve real-time intracorporeal imaging (US), which can be challenging due to patient motion, tissue deformation, and operator variability in reaching the target with the percutaneous needle [18]. Therefore, these assistance systems aim to improve accuracy by providing visual guidance during needle insertion, ensuring precise targeting of lesions or anatomical structures. Likewise, novice surgeons and operators benefit from image-based assistance, as it helps them to place needles accurately.

Regarding the development of the liver phantoms, after the initial development of the paraffin-based phantom (Figure 6), it was evaluated by US imaging, and it was found that, due to the poor echogenic properties of the phantom, the lesions inside it could not be visualized. The authors think that this fact was mainly due to poor hydration with the paraffin. For this reason, we proceeded to address the phantom design by using a solution based on gelatin to mimic the parenchyma tissue. This solution showed better echogenic properties when visualized by ultrasonography. The lesions were adequately visible, so it was the solution used in the study as a working environment (Figure 7). Table 1 summarizes the features of both phantoms developed.

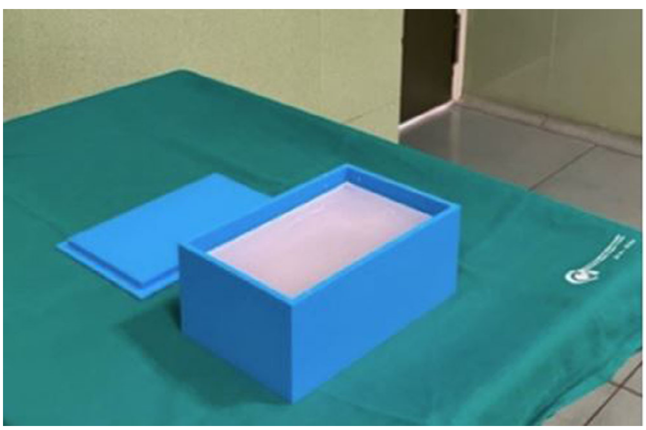

FIGURE 6 Paraffin-based liver phantom.

FIGURE 7 Gelatine-based phantom.

TABLE 1 Comparison of paraffin phantom and porcine gelatine phantom.

Type of phantom	Materials	Limitations	Visualization
Paraffin-based	PLA mold printed in 3D – Candle gel sephadex	– Air bubbles – Opaque layers	Low echogenic properties
Gelatine-based	– Porcine gelatine – Lesions created with agarose, glycerol, and sephadex – 3D-printed vascular structures with TPU	– Tendency to create foam that hinders the creation of multiple layers – Early expiration	Adequate visualization of both the artificial lesions and the blood vessels

Abbreviation: PLA, poly lactic acid.

Acquisition of US images is a straightforward process. However, transmission of these images to a computer for its process using 3D Slicer requires a video capture system, which increases the level of complexity of the process. A Python script was needed to create a socket to stream this image, followed by the configuration of the OpenIGTLink module in 3D Slicer as a client. Precise definition of the image transformations in 3D Slicer was crucial for proper visualization. Careful attention to detail, both in the Python script and in the 3D Slicer transformation hierarchy, is necessary to ensure that the system works correctly. Table 2 shows the two video capture options analysed for this study. Both have perfectly met the needs, but the Unotec option was chosen because it was more economical and compact. For the rest, both systems do not differ in other functionalities.

TABLE 2 Features of the different video capture devices analysed for this study.

Feature	Aver media	Unotec Converty II
Maximum resolution	4k at 30 FPS	FULL HD 1080 AT 60 FPS
Passthrough	4k at 60 FPS	1080 at 60 FPS
Connection interface	USB 3.1	USB 2.0
Video inputs	HDMI	HDMI
Video outputs	HDMI	HDMI
Compatibility	Windows, MacOs	Windows, MacOs
Additional features	Live streaming	Live streaming

TABLE 3 Comparison of the different platforms for streaming HoloLens 2 glasses

App	Direction	Real time	Functionality
FMETP	Bidirectional	No	No
Holographic RemotingPlayer	PC to HoloLens 2	Yes	No
Mirage	PC to HoloLens 2	Yes	Yes
OBS Ninja	Bidirectional	Yes	No
MicrosoftMesh	HoloLens to HoloLens	–	–
Microsoft Remote Asist	Bidirectional	–	–

Note: Not available information has been indicated by '–'. The parameters 'Real time' indicates whether the tool provides or not video streaming in real time and 'functionality' refers to the capacity for manipulating and interacting with virtual monitors from your HoloLens 2 glasses.

After carrying out an exhaustive analysis of various options to visualize the 3DSlicer interface with the tracking system through the HoloLens device, the Mirage platform was chosen as the one that best meets all the necessary requirements. Table 3 shows the different options analysed and their main features.

NDI Aurora system was selected for its reliability and accuracy, as well as ease of use. For the file configuration for Plus Server, the two elements to be tracked (US probe and needle) and the port (different to the port of python script for the US image) and IP address (localhost) for the connection in 3D Slicer should be defined. Once the IGT module was configured, the 3D model (*.stl) of the US probe was integrated into 3D Slicer, as well as the corresponding US image plane. The correspondence between the 3D model of the US probe with the Aurora sensor location, as well as between the US image plane and the 3D model of the US probe, was carried out using a hierarchy of linear transformations. These transformation matrices were previously calculated by a calibration process. Thus, the intracorporeal needle, the US probe, and the US image can be visualized in real time in 3D Slicer with high accuracy in a simple way by using NDI Aurora tracking data as a feed (Figure 8).

After integrating all the elements of the system, we obtained a complete system capable of capturing in real time both the US image and the position of the surgical instruments intraporporeally and visualizing them holographically on the real surgical environment (Figure 9). This allows the clinician to have at all times a spatial relation of the US image with respect to the intracorporeal needle during the procedure. Although it is necessary to use EM tracking sensors, the system was feasible and easy to use. It should be noted that the developed solution can be used with any US imaging device.

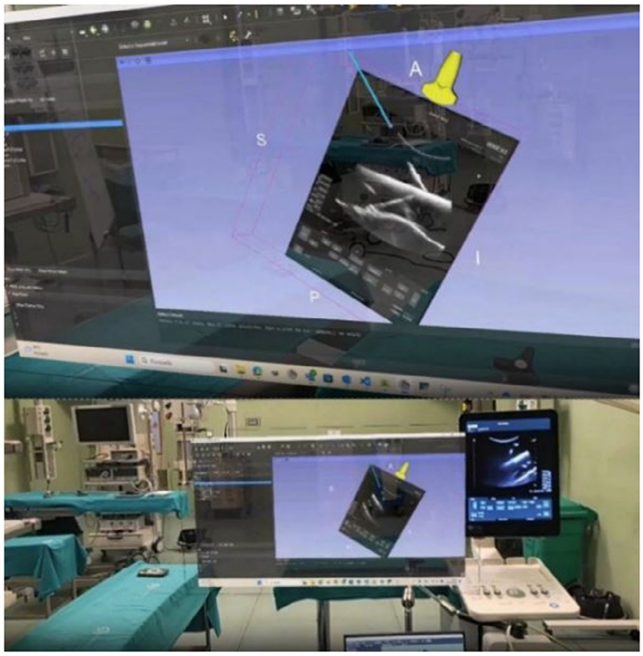

FIGURE 8 Interaction between HoloLens and 3D Slicer.

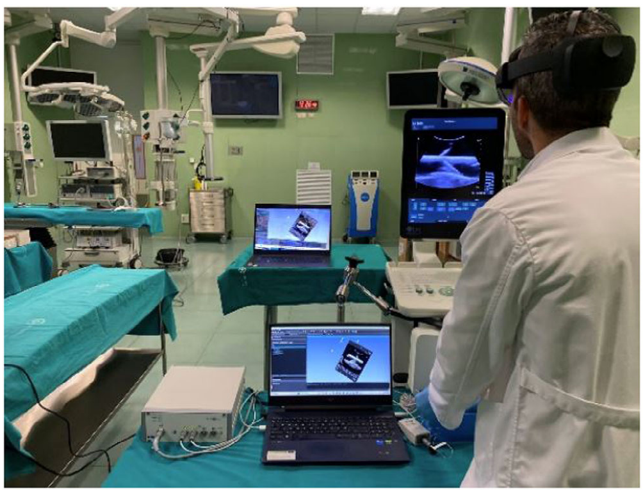

FIGURE 9 The complete integrated system.

Table 4 shows the score obtained in relation to the experience of using the assistance system. In general, the participants considered the use of the EM tracker and the identification of the lesion to be easy. In addition, they considered the proposed systems useful as a training tool, including the liver phantom, and the usefulness of MR technology for assistance in

TABLE 4 Data on the preliminary subjective validation of the system.

Subjective validation aspect	Mean	SD
Aurora NDI system complexity	2.33	0.82
Lesion identification complexity	2.00	0.89
Utility for training	4.17	1.09
Phantom	4.05	0.52
Use of mixed reality glasses for puncture	4.67	1.21
Utility of MR for surgical assistance	4.50	1.22

Note: This table shows the weighted mean and standard deviation (SD) of the responses collected by means of a form. The score ranges from 1 (minimum) to 5 (maximum).

percutaneous interventions. Users consider the use of MR a positive ergonomic aspect during US visualization.

Comparing the developed assistance system with others presented in the scientific literature, we can observe that some of the technologies used in this work have been applied individually. However, to our knowledge, a work integrating all of them for the development of an assistance system for percutaneous liver surgery based on AR and US has not yet been presented.

Thus, Ungi et al. [14] applied Slicer IGT and Lump Nav for the development of their system, although they did not provide visualization using AR. On the other hand, Léger et al. [15] applied Open IGT Link and Plus Toolkit for the development of their assistance system for US-guided puncture, although in this case focused only on neurosurgery. Diez de lastra et al. [19] designed and developed an assistance system for pedicle screw placement, but outside the application in percutaneous interventions. Beyer et al. [16] develop a system based on preparative CT images, without the possibility of use with intraoperative US imaging. Lau et al. [20] provided a system based on laparoscopic videos and real-time US; however, they do not mention its application with AR. A system for percutaneous surgery based on AR and US that indicated some trajectories and the quality of trajectories in surgeries was developed by Schwenderling et al. [21]. Nevertheless, they fail to confirm or address solutions for particular applications, such as liver injuries.

Considering some scientific reviews, Mangalote et al. [22] pointed out the use of US as an imaging technology for percutaneous surgery providing good visualization, easy and safe accessibility with real-time guidance, widely available, cost-effective, and without radiation exposure. These reasons make US imaging the most popular and accessible imaging technology for percutaneous surgery. The main risks of using US needle guidance are related to the high operator dependency, as it requires adequate training and a high level of clinician skill [23]. On the other hand, AR can be used to enhance the visualization of US images, creating a realistic assistance and training scenario and allowing the evaluation of the novice clinician, providing feedback to help improve their skills [24].

For future work, it is proposed to carry out an apparent validation of the system with a larger number of medical professionals such as clinicians with expertise in US-guided interventions, as well as with residents and medical students, as potential end users of this system. Once this validation is completed, a final validation will be carried out in an experimental clinical setting.

This study has presented the development, verification and initial testing of an assistance system for percutaneous interventions based on AR and US imaging. However, it should be noted that several challenges remain to be addressed for the full integration of AR technology in clinical settings, as well as the complexity associated with soft tissue registration [25]. In surgery, soft tissue registration poses a complex challenge attributed to the deformations experienced by the patient during surgery due to postural changes or breathing. These will be issues to be addressed in future developments and in a clinical environment. Thus, some parameters will be taken into account in the future evaluation of our percutaneous surgical assist system. Some of these parameters should be: the ease of use of the system display, the capacity of manipulating and interacting of the system from the AR, the safety of the needle use, the skills of the clinical and surgeons, the future use clinical of our system, and the global visualization through the use of our system [26].

4 | CONCLUSIONS

In this study, we have presented the first steps for the implementation, configuration, and integration of a mixed reality-based assistance system for percutaneous hepatic interventions guided by US. Several liver phantoms have been developed for the setup, being the one based on gelatin the one that has given us the best results in terms of echogenic properties. In the same way, several solutions have been implemented for mixed reality visualization, being the Mirage application the one that has yieled the best results in terms of simplicity, image quality, and video transfer speed. The system allows the clinician to know in real time, and on the real image of the patient, the position of the intracorporeal needle with respect to the US image plane, which would not be possible in a traditional intervention. The development of image-based support systems for US-guided percutaneous interventions lays the foundation for increasing accuracy, reducing errors, and improving surgical outcomes, as well as contributing to safer and more effective procedures.

AUTHOR CONTRIBUTIONS

Lucía Salazar Carrasco: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; writing—original draft; writing—review & editing. **Ignacio Sánchez-Varo**: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; writing—original draft; writing—review & editing. **Daniel Caballero Jorna**: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; writing—original draft; writing—review & editing. **Amaia Iribar-Zabala**: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; supervision; validation; writing—original draft; writing—review & editing. **Álvaro Bertelsen-Simonetti**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; software; supervision; validation; writing—original draft; writing—review & editing. **Juan A. Sánchez-Margallo**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; writing—original draft; writing—review & editing. **Francisco M. Sánchez-Margallo**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; software; supervision; validation; writing—original draft; writing—review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Lucía Salazar Carrasco https://orcid.org/0009-0007-5889-0658
Ignacio Sánchez-Varo https://orcid.org/0009-0002-8913-0292
Daniel Caballero Jorna https://orcid.org/0000-0003-2822-0323
Amaia Iribar-Zabala https://orcid.org/0009-0000-4445-6622
Álvaro Bertelsen-Simonetti https://orcid.org/0000-0003-2421-9202
Juan A. Sánchez-Margallo https://orcid.org/0000-0002-0100-2695
Francisco M. Sánchez-Margallo https://orcid.org/0000-0003-2138-988X

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