Sensing Technologies for Guidance during Needle-based Interventions

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***Abstract*—Needle intervention is widely employed in clinical practices such as biopsies, regional anesthesia, blood sampling, neurosurgery, and brachytherapy. Traditional needle insertion relies on surgeon expertise and kinesthetic feedback, yet accurately targeting deep tissue structures remains challenging. To address this, significant research has advanced sensing technologies to aid insertion accuracy. This paper comprehensively reviews recent developments in needle insertion sensing techniques, encompassing needle tip position tracking, proximity measurement, and puncture detection. It evaluates these methods across metrics including accuracy, cost-effectiveness, portability, compatibility, noise resistance capability, Technology Readiness Level (TRL), and future trends. Emerging research directions highlight advancements in machine learning integration, miniaturization, and enhanced multimodal sensing capabilities to improve procedural outcomes and expand application domains.**

***Index Terms*—Biomedical sensor, needle tip tracking, proximity sensing, puncture detection, image-guided insertion.**

I. INTRODUCTION

Many medical procedures involve inserting a thin tubular device deeply into soft tissue, often with the goal of reaching a specific target. Considering different medical procedures that involve needles, it is estimated that over 16 billion injections are performed annually worldwide [1].

Depending on the specific medical task, different needle gauges are chosen, and the precision required to target the desired tissue may vary. (Fig. 1) [2]. In clinical practice, there is no universal standard for insertion accuracy. Nevertheless, the required level of accuracy is generally high, yet it's modulated by the goal of the procedure. For instance, millimeter precision is typically needed for biopsy, brachytherapy, and anesthesia, while micrometric precision may be desirable for procedures involving the brain, fetus, eye, and ear. Conversely, in scenarios like insulin injections, a less stringent level of accuracy may suffice. Furthermore, the target area may be in proximity of crucial structures such as vital organs, vessels, or nerves. In such cases, extreme caution must be exercised to prevent any harm or the spread of disease, as this could result in adverse events and complications.

In fact, precisely guiding a needle to its target presents several challenges. A primary difficulty lies in accurately identifying and localizing targets such as deep vessels or lesions embedded within tissue intraoperatively. Nevertheless, over recent years, a variety of advanced technologies has emerged to aid in this crucial identification and localization process [3]. For instance, medical imaging facilities are commonly used for providing real-time tissue target visualization, providing dynamic feedback during needle insertion. The major hurdle arises from the limited needle tip perception once it penetrates the tissue. Often, subsequent insertion relies on the practitioner's mental visualization of the soft tissue bulge and ambiguous tactile perception. Additionally, soft tissue deformation during insertion introduces unpredictability, making it more challenging to interpretation of the needle's trajectory. The interaction between the needle and tissue can cause further deflection of the needle during insertion, potentially complicating the procedure.

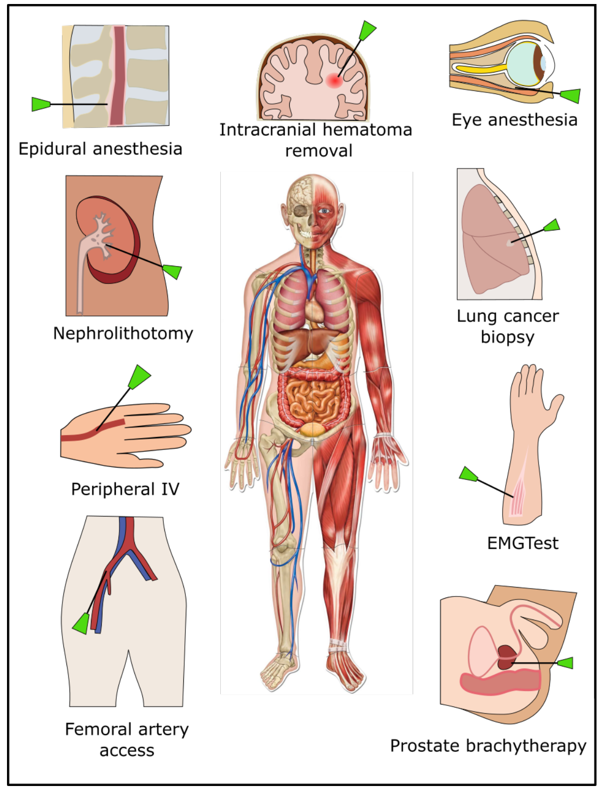

Fig. 1. Needle interventions are widely used in a diverse range of medical procedures, from biopsies to regional anesthesia.

In light of the above complexities, the integration of assistive sensing technologies becomes crucial in overcoming the inherent limitations of human perception and refining the precision of needle insertion procedures. Conducting a comprehensive review of current sensing technologies utilized for guiding needle insertion towards tissue targets, along with a discussion on their attainable limits, would prove to be

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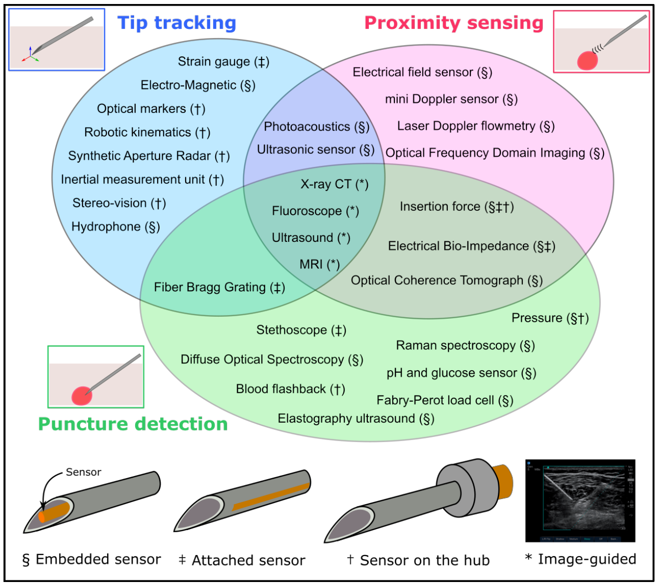

Fig. 2. Sensing technologies are grouped into three categories based on their purpose: tip spatial tracking, target proximity sensing, and puncture detection. Additionally, the sensor implementation methods are labeled as: embedded sensor, attached sensor, sensor on the hub and image guided.

beneficial. In a previous review, such as [4], the focus is on discussing the application of various sensing techniques in monitoring extravasation events in needles. The technologies that have been reviewed are inspiring, even though the assisted medical procedure differs. The article [5] discusses the use of integrated sensors on needles to detect different physical properties of tissues they touch. These related technologies will be discussed in this review paper. To the best of our knowledge, there are no existing papers that summarize modern sensor techniques for precise needle insertion guidance.

This paper aims to fill this gap and provide an extensive review of the existing sensing technologies for guiding needle insertion. Thus, a systematic literature review was performed using the keywords: *(needle AND (sensing OR tracking OR localization OR proximity))*. The search excludes keywords such as *"cell"*, *"microneedle"* and *"suture"* since the focus of this review is on sensing technologies applied to percutaneous needles. The search was conducted in year 2023, and the literature search included both journals and conference proceedings in the IEEE, Scopus, and Google Scholar database. Only English publications were considered. Given the focus of this review on technological research, PubMed and patent database were not considered as primary sources but not excluded. The involved databases returned 290 results, among which 130 papers were selected. This selection aimed at including papers describing technical developments and system characterizations in related topics. Only a few medical papers were included to demonstrate technology efficacy. If multiple papers were reported from the same research group on the same technology, only the latest or the most completed publication was selected. Considering their applications across different guidance procedures, the reviewed technologies are categorized into three main groups, as also shown in Fig. 2:

*1) **Needle tip spatial tracking**:* Needle tip spatial tracking is the process of accurately locating and monitoring the position of the tip of a needle in real-time.

*2) **Target proximity sensing**:* Target Proximity Sensing refers to the capability of detecting the approach of the needle tip towards the target during the insertion procedure. In certain cases, the sensing technologies can also offer precise measurements of the distance between the needle tip and the target.

*3) **Puncture detection**:* Puncture detection refers to the identification of a change in tissue type at the needle tip, signalling a puncture event or the needle's entry into a different tissue layer.

In Fig. 2, different sensing technologies are marked by labels according to their implementation methods. Specifically, we use *Embedded sensor*, *Attached sensor*, and *Sensor on the hub* to denote sensors that are integrated within the needle lumen close to the tip, assembled on the needle tube, and connected to the end of needle hub respectively. Additionally, *Image-guided* is used to label sensing methods based on external medical imaging modalities.

II. Needle Tip Spatial Tracking

The goal of needle tip spatial tracking is to acquire the position and/or orientation of the needle with respect to a reference coordinate system. Such information is essential for guiding the needle accurately to a desired target, especially in the context of image-guided procedures or robotic needle insertions.

A. Embedded sensor

*1) **Electro-Magnetic (EM)**:* The EM sensing modality includes a magnetic field generator and a small magnetic (hall effect) sensor embedded in the needle. The magnetic field interacts with the magnetic sensor, enabling the measurement of the needle position and orientation real-time.

Most related insertion guiding systems were developed based on commercial EM tracking systems such as the 3D Guidance from NDI Inc., Canada (Fig. 3(b)) [6] and the Anser system [7]. Alternatively, previous solutions have investigated customized designs to adapt to various applications. Zhao *et al.* have developed a clip-on EM sensor which can attach to the needle shaft for tracking [8]. Related solutions also consisted of using both permanent magnetic needle [9] and active magnetized needle [10].

The accuracy of EM tracking systems is reported ranging from 1 to 2 mm [11], [12], [13]. However, despite advantages such as good accuracy and miniaturization potential, this sensing modality requires the generation of an EM field in the clinical environment. Therefore, potential EM interference on other clinical devices should be carefully considered.

*2) **Acoustics**:* Another popular method for needle tip tracking is through acoustic sensing, typically in the ultrasonic range. Sound waves is generated by an Ultrasound (US) transducer and propagating in the tissue area of interest. As shown in Fig. 3(a), an acoustic sensor such as a piezo element [14] or hydrophone [15], is embedded in the needle tip to convert the sound waves to an encoded electric signal, which can be used for estimating the needle tip location. Study [16] developed a tip-tracking technology based on a new needle incorporating a piezo element 2–2.3 mm from the tip. This element was activated by US and produced a coloured circle surrounding the needle tip on the US image, facilitating real-time tracking. This innovation has reported promising improvements in the performance of sciatic blocks. A related commercial technology is Onvision (B. Braun AG, Germany), where a piezoelectric sensor is wrapped around the needle close to the tip for its tracking [17]. With a similar principle, acoustic signals can be generated and emitted from the needle tip through a pulsed laser. These acoustic signals are then detected by an external US transducer to derive the tip position [18]. This technique is based on photoacoustic effects.

*3) **Optical tracking**:* In [19], Cheng *et al.* presented a tip tracking method through processing scattering imaging, which is created by an optical fiber-equipped needle onto the tissue surface. The proposed method is found able to provide real-time tracking of the needle tip's position and orientation up to 3 cm depth with an averaging 2.0±1.2 mm (positional accuracy) and 0.16±0.1 rad (orientation accuracy).

B. Sensor on the hub

*1) **Optical tracking**:* A common method for tracking the needle spatial position is achieved by attaching reflective markers onto the needle holder, which are monitored by external cameras (Fig. 3(c)) [20], [21], [22], [23]. Typically, such optical markers can achieve tracking accuracy at the sub-millimeter level. Study [24] has even demonstrated the application of such a technique in microsurgery with a tracking error of about 5 μm. Nonetheless, this method often overlooks needle deflection. When this technique is applied to thin and long needles, the tracking accuracy might be compromised. Recent researches have also explored the use of color markers [25], AruCo markers [26] and optical 3D pose trackers [27], which may achieve similar tracking effectiveness with a more compact system.

*2) **Other sensors**:* In addition to the above, study [28] presented an IMU-based surgical assistance method for minimally invasive puncture for intracranial hematoma. A similar approach was also applied in percutaneous interventions as presented in [29]. Another research [30] explored the use of Ultra-Wideband (UWB) circular Synthetic Aperture Radar (SAR) for tracking biopsy needles with millimeter-level accuracy. In addition, a miniature visual tracking system was introduced in [31], where a miniature video camera was mounted on the needle hub for estimating the needle location and orientation relative to a skin-attached sticker with color reference markers. Finally, robotic assistance in biopsy procedures has recently gained traction. For example, the use of robotic kinematics for tracking the needle tip was demonstrated in [32].

C. Attached sensor

In many cases, attached sensors are used for needle shape sensing. Given the estimated shape of the needle and the position of the needle holder, the spatial location of needle tip can be estimated. In addition, needle deflection can be estimated based on the sensed force and moment at the needle base by implementing beam deflection theory [33]. However, it is important to note that this estimation may not be completely accurate due to the complex nature of needle-tissue interaction. Therefore, methods for improved shape sensing have been researched in the past decades. These are presented below.

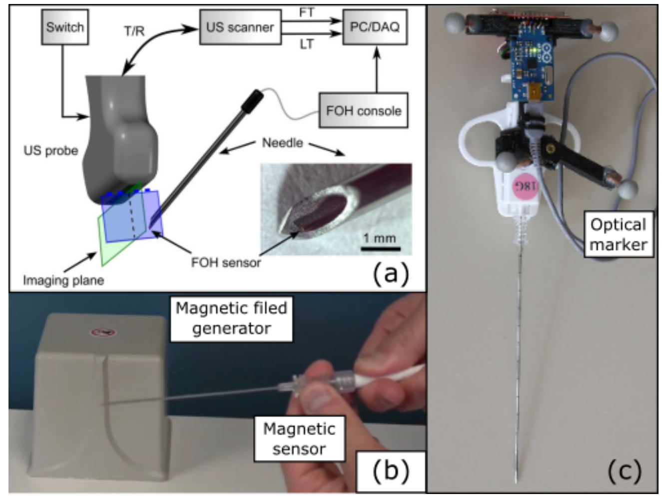

Fig. 3. Typical sensor technologies used for needle tip tracking include (a) acoustics [15], (b) EM sensors (NDI Inc.), and (c) optical markers on the needle hub [22].

*1) **Fibre Bragg Grating**:* One of the most common methods for needle shape sensing is through attaching optical fibers with Fibre Bragg Gratings (FBG) to the needle shaft. FBG is a type of optical sensor that detects changes in the wavelength of light reflected by FBG elements [34]. The needle deflection causes a slight change in the wavelength of reflected light, which is detected in real-time by the FBG sensor system. By analyzing these changes, the angle and magnitude of the deflection can be measured in real-time. Thanks to its miniature size and high precision, built-in FBG needles have been successfully used for real-time epidural space identification [35] and applied to various medical procedures such as arterial puncture [36] and lumbar puncture [37], epidural anesthesia [38], transperineal prostate needle placement [39], and brachytherapy [40]. Additionally, FBG sensors are compatible with Magnetic Resonance Imaging (MRI), facilitating applications in MRI-guided interventions [41]. Despite these advantages, the use of FBG sensing technology may be limited due to its high cost, fragility, sensitivity to temperature changes and limited dynamic range [42]. Normally, 3 to 4 FBG fibers are embedded for temperature compensation as shown in Fig. 4(b) [43].

*2) **Other optical sensing technologies**:* Similarly to the discrete strain measurements in FBG technology, optical frequency domain reflectometry (OFDR) is an alternative method to measure the distributed strain along the fibers [47]. In addition, an integrated reflective fiber optic sensor based on a Fabry-Perot cavity can be used for shape sensing, as presented in Fig. 4(c) [48], [45]. The Fabry-Perot cavity consists of two parallel reflecting surfaces (mirrors) that allow multiple reflec-

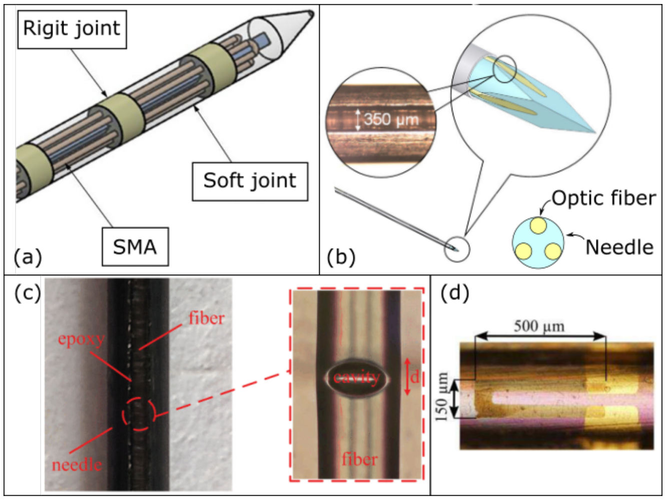

Fig. 4. Examples of needle shape sensing methods. (a) Three SMA wires are embedded inside an active needle. The needle tip position can be estimated via the SMA's electric resistance [44]. (b) Multiple FBG fibers are attached to the needle tube for needle shape reconstruction with temperature compensation [43]. (c) Schematic of the sensing technique based on Fabry-Perot cavity [45]. (d) The needle shape can also be measured via the attached strain gauges [46].

tions of light, enabling the measurement of needle deflection based on changes in the interference patterns.

*3) **Strain gauge**:* Strain gauge measures changes in electrical resistance resulting from object deformation. When a strain gauge is attached to the surface of a needle, any deflection during insertion alters the strain gauge's resistance. This change can be thus used for calculating the amount of deflection along the needle axial direction [49]. In [46], Robert *et al.* presented a design with 3 micro-gauges to reconstruct needle deflection (Fig. 4(d)). In another study [50], printed strain gauges on biopsy needle was presented to sense needle deflections and a resolution of 500 μm was achieved.

Similarly, in [44] (Fig. 4(a)), a 3D steerable active flexible needle with shape memory alloy (SMA) actuators was proposed. Through self-sensing electrical resistance of the SMA device, accurate needle shape estimation was demonstrated.

D. Visualization in medical imaging

Medical imaging modalities such as US, fluorescence CT, and MRI are extensively used to supervise needle insertion processes [51], [52]. During an image-guided needle insertion procedure, the operator localizes both needle and target in real time in the image in order to navigate the needle accurately. While medical imaging modalities have been found helpful, supplementary technological aids are often required to discern the needle within the image.

*1) **Ultrasound Imaging**:* Imaging from high-end US devices can offer high-resolution visualization of the needle and surrounding tissues, facilitating the visualization of needle in biopsy or therapeutic procedures [53]. Nevertheless, US images are often noisy, so methods to alleviate the challenges in identifying the needle's position are often required. One of such techniques is contrast-enhanced US which employs contrast agents to increase the contrast between the needle and surrounding tissues [54]. Additionally, related approaches involve the use of a contrast bubble [55], needle with corner cube reflectors [56], and needles with excitation buzzer [57].

Most US devices can only display a 2-dimensional (2D) sectional view to the physician. This 2D representation necessitates the manual manipulation of the US probe in both transversal and longitudinal directions in order to localize the needle tip. An additional cognitive burden arises from the need to distinguish between the needle shadow and the echo shadows reflected from different tissue types in US imaging. The inherent limitations of 2D US motivate the recent development of advanced 3D US devices, which show significant impact in enhancing the precision of needle tracking and placements [58]. Additionally, study [59] demonstrated the potential of a miniaturized 3D US probe, enabling its application in transrectal needle guidance.

*2) **Fluoroscopy and Computed Tomography**:* Fluoroscopy primarily utilizes X-rays to create real-time imaging. This technique is commonly used in interventional radiology procedures, to show and successfully track the needle tip [60]. Study [61] demonstrated its applicability in percutaneous orthopedic interventions using C-arm system, achieving a tracking accuracy of 3.2 ± 2.7 mm. In another research [62], application of CT in 3D motion-compensated needle guidance for transjugular intrahepatic portosystemic shunt (TIPS) procedure has been proposed with an accuracy of 1.22 mm.

*3) **Magnetic Resonance Imaging (MRI)**:* MRI provides superior soft tissue contrast compared to both US and X-ray imaging, with the benefit of avoiding ionizing radiation. Particularly, MRI is considered when the target anatomy is complex, interactive visualization of needle tip is required, and multiple needles are tracked simultaneously [63]. Also, MRI can deal with both needle material variations [64] and depth of visualisation [65]. According to [66], MRI's ability to visualize needles at significant depths within the body is particularly valuable in vascular interventions and deep-seated tumors, which are challenging for other imaging techniques.

*4) **Needle tip detection algorithms for medical imaging**:* In order to accurately identify the needle's tip from the medical imaging autonomously and in real-time, recent studies have advanced various algorithms including intensity-based methods like thresholding, gradient methods, Hough transforms, edge detection, and feature extraction, as well as advanced approaches like pattern matching, Kalman filtering, and deep learning. Given this paper's aim to survey various sensing technologies for guided needle insertion, we provide only a selective overview of typical algorithmic methods based on medical imaging for needle segmentation. For a more systematic review, readers may refer to other papers on the topic [67].

More specifically, authors in [68] presented an optical flow algorithm to track needle features in US images by employing the Circular Hough transform to precisely identify the needle tip, even when imaging was performed from an out-of-plane perspective. Through experiments conducted within tissue phantoms and ex-vivo studies involving bovine kidneys, they successfully validated the effectiveness of the proposed tracking method. Study [69] developed an algorithm that merges a weighted RANSAC curve fitting method with a probabilistic

Hough transform. Their approach has been demonstrated to accurately track the needle tip in 2D US images, even when the needle bends during insertion. Margallo *et al.* in [70] applied a block-matching-based registration method to US images post-Hough transform. This technique successfully achieved effective tracking for needles varying in size, material, and surface condition. Also, authors in [71] performed tracking of needles in robot-assisted intervention using 2D US feedback, integrating image processing for region of interest selection, Kalman filtering for tracking and a needle-tissue interaction model. The method allowed accurate needle tracking, predicting deflection, steering the needle through US feedback and preventing tissue deformation by pausing the needle at specific depths.

Furthermore, deep learning algorithms are developed to assist in predicting the optimal needle insertion point and trajectory for needles based on patient-specific data, enhancing the overall accuracy of needle injections. Such predictive models can incorporate features like patient anatomy, needle characteristics, and procedural history. At the same time, image processing techniques can provide denoising and contrast enhancement to improve the quality of the image [72]. For instance, Multilayer Perceptron (MLP) network and Kalman filter for needle detection and tracking were used in [73]. While tracking performance was not yet optimal, the approach showed the usage of MLP as an alternative for improving needle detection through per-pixel classification, leading to improving tracking accuracy in US-guided procedures. Additionally, enhanced needle localization may involve complex imaging formats, such as 3D ultrasound, which compiles sequential 2D images captured at various depths or angles, or temporal image sequences. For instance, semantic segmentation using Concurrent Spatial information [74] and attention U-Net [75] has been successfully applied for needle detection in US images. Similarly, in [76], an algorithm combining patch classification and semantic segmentation was developed for localizing needles in 3D US volumes with high precision. In transrectal ultrasound (TRUS) application, study [77] developed a 3D-CNN method to find and localize needle based on a sweep of TRUS images. In study [78], a transformer-based method to US images was made to fuse information from a template update module to enhance needle tip visualization and a historical data analysis module to accurately track the needle tip's position.

III. Target proximity sensing

Target proximity sensing during needle insertion is a critical aspect in many medical procedures. Specifically, the relative position or distance between the needle tip and the target tissue is sensed. This information is essential in needle insertion control, and minimizing the risk of puncturing critical tissues. It is worth noting that medical imaging such as US, MRI and CT can provide this information (as presented in Section II-D), and they will not be discussed in this section. This section will focus on different embedded sensors at the needle tip and sensors on the hub for proximity detection purposes.

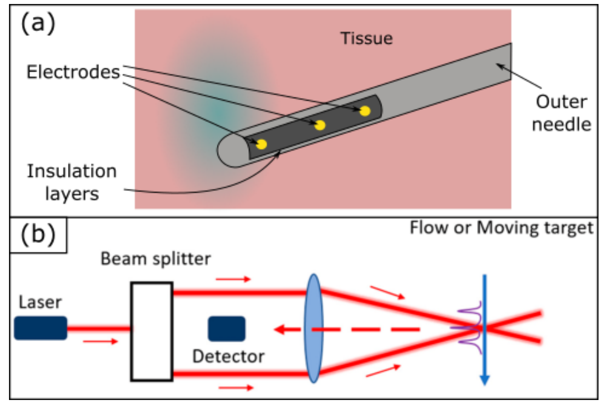

Fig. 5. Principles of example methods for target proximity sensing during needle insertion based on (a) electrical field measurement and (b) laser Doppler.

A. Embedded sensor

*1) **Doppler effect:*** The Doppler effect describes the shift in frequency or wavelength of a wave relative to its receiver. This method works particularly effective when targeting blood vessels due to the inherent movement of blood flow. Primarily, US waves are generated using a miniaturized Doppler sensor situated within the needle's lumen, protruding slightly from the needle tip. This sensor emits acoustic waves and captures their echoes, based on which the relative distance between the needle tip and the non-homogeneous tissue structure can be estimated [79]. A similar design was presented in study [80], where a PZT element was embedded at the tip, backed by a magnet wire material, achieving a remarkable 0.95 mm sensing accuracy. Alternatively, lasers can be employed to generate the necessary waves, a technique often referred to as Laser Doppler flowmetry, as shown in Fig. 5(b). In this method, a laser is emitted from the needle's lumen, scattering upon contact with blood cells. The resultant signal provides insights into the needle tip's position relative to blood vessels [81].

*2) **Electric field:*** In scenarios involving the use of needle electrodes, the needle itself can be used to measure the surrounding electric field within the tissue or produce electrical stimulation. Study [82] proposed to estimate the proximity to a target nerve by modulating the stimulation current level until a neural response was detected (Fig. 5(a)). The results showed great potential in assisting brainstem biopsies procedure. As described in [83], the measured electrical bioimpedance (EBI) value is associated with the generated electrical field by the needle electrode. This indicates the ability to sense a volume of tissue around the needle tip. Zhang *et al.* [84] detailed the application of a needle electrode-based EBI technique during neuron insertion. The EBI signal could be used for assuring the needle contact with the neuron membrane without damage, eventually improving the neuronal patch clamping procedure. Another study [85] leveraged this sensing approach to guide needles in vitreo-retinal micro-surgery, demonstrating its efficacy in halting the needle at a safe distance before reaching the retinal vessel.

*3) **Optical sensing:*** Another popular optical sensing method for target proximity sensing is Optical Coherence

Tomography (OCT). This technology uses low-coherence interferometry to capture high-resolution, cross-sectional images of biological tissues. By incorporating OCT into the tip of a needle, real-time imaging information of the tissue in front of the needle can be obtained. Study [86] presented a method with an optical needle dynamically moving inside another needle to generate 3D OCT visualization, demonstrating its capability to image tissue with a depth of 2–3 mm from the needle tip. In another study [87], the OCT technique was implemented for enhanced needle control as it approached critical tissue such as endothelium within 50 μm. Wang *et al.* demonstrated the application of OCT for safely guiding veress needle insertion [88]. Empowered by a convolutional neural network (CNN), their OCT-based tissue classification and distance estimation demonstrated an accuracy of 36 μm. Similarly, study [89] used Optical Frequency Domain Imaging (OFDI), also known as high-speed second-generation OCT, for imaging tissue micro-structure to about 3 mm depth during a biopsy procedure.

Another optical method used for target proximity sensing was proposed in [90]. In this case, the authors embedded two optical fibers within the needle lumen to generate and receive US signals, which were produced by a pulsed laser. This design was tested in a cardiac intervention setup and demonstrated the ability to measure the distance from the needle tip to the cardiac wall, achieving a US imaging depth of up to 2.5 cm. The system exhibited an axial resolution of 64 μm.

*4) **Electro-Magnetic**:* As mentioned in Section II, researchers have developed a tracking method based on a passive magnetic needle and an external magnetic sensor. Study [91] extended such method and integrated the EM needle tracking to a US device. Through registering the tracking information to the US imaging, target proximity could be thus estimated. Significant improvement in needle procedure based on porcine phantoms was reported compared to the conventional US group, with an overall 57.1% lower distance to target.

B. Sensor on the hub

In addition to the above, study [92] presented a haptic sensing system for guiding needle insertion in medical procedures like epidural anesthesia. OCT sensor was embedded in the needle to measure the the force acting on the needle. Then machine learning algorithm was leveraged to analyze the force readings, and thus estimate its distance to the boundary layers before physical contact. This sensing method was integrated to a robotic system and tested with phantoms mimicking epidural cavity structures. The results indicated a success rate of 96% in cases using proximity-based haptic feedback, which was a substantial improvement over methods with only visual feedback.

IV. Puncture detection

Identification of different tissue types at the needle tip is critical for the success of needle placement into a target, especially when the target tissue is small or deep-seated. The detection of target tissue in real-time can be used for needle insertion control and stopping its advancement. Essentially, tissue differentiation is accomplished by detecting its inherent physical properties, such as mechanical, optical, and electrical characteristics. Potentially, the medical image-guided method can indicate needle puncture of a target, as already described in Section II-D. The other prevailing sensing methods are summarized as follows.

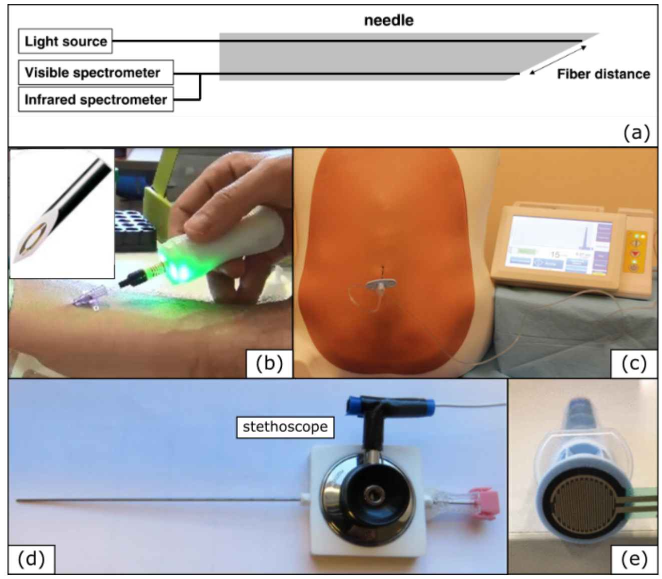

Fig. 6. Examples of sensing technology for puncture detection: (a) DOS based on embedded optical fibers inside the needle lumen [93]; (b) EBI with a concentric needle electrode; (c) the CompuFlo® dynamic pressure monitoring system (Milestone Scientific Inc., US) [94]; (d) Stethoscope attached on the needle shaft for audio signal monitoring [95]; and (e) a force sensor attached to the needle hub to monitor changes in insertion force [96].

A. Embedded sensor

*1) **Force sensing**:* One common method for puncture detection is sensing the forces acting on the needle. This assumes that the target tissue region has different mechanical properties than its surroundings, or is covered by a tissue with different properties, which can vary based on tissue density, viscosity, and composition [97]. This change can be measured and used to determine when the needle has successfully entered the target tissue [98]. Studies have successfully developed needle with tip force sensing capability by integrating a Fabry-Perot load cell [99], [100] or piezo element [14], [101] inside the needle, close to the tip. This technique has been used in percutaneous procedures such as biopsy and electrodes placement for electrical stimulation or ablation.

*2) **Pressure sensing**:* Another technique involves measuring the pressure changes that occur as the needle tip passes through the various layers of tissue. Sensors can be placed within the needle lumen to detect these pressure changes. As the needle tip approaches and punctures the target tissue, a change can be measured in some applications. This is particularly the case in epidural injections, as the pressure in the epidural space is usually lower than that of surrounding tissues [102]. This technique has also been demonstrated for the detection of intraneural and intravascular access [103]. A commercial device CompuFlo® from Milestone Scientific Inc. as shown in Fig. 6(c) was used in the study. For the success of implementing this technique, different factors should be taken into consideration including needle diameter, needle tip location, type of target tissue, and flow rates [104].

*3) **Optical Spectroscopy**:* Owing to their distinct compositions, different tissue types also exhibit significant differences in light transmission and reflection properties. Leveraging these unique optical properties, accurate tissue identification can be realized. This is normally done with an optic needle, where light can be transmitted to the needle tip through an optical fiber inside the needle lumen and also the reflecting light can be received. This technology finds applications in intravenous access, biopsy and tumor ablation procedures, providing confirmation on the needle position within the desired tissue. As illustrated in Fig. 6(a), study [93] proposed the use of Diffuse Optical Spectroscopy (DOS) based on a special needle with two fiber optics in its core, one for emitting light and the other for receiving light. By analysing the response under a wide spectrum, the tissue type contacting the needle tip could be identified. In study [105], a fiber-optic interstitial needle that carry hypoxia-sensitive fluorescent probes was used for cancer sensing. The fluorescent probe could rapidly scout the nearby hypoxia markers within the tumor. In addition, other related technologies using the tissues' optical properties in puncture identification include OCT [106] and Raman spectroscopy [107]. In [108], a sensitivity of 91.2% and a specificity of 97.7% was reported in blood vessel puncture detection based on an OCT needle.

*4) **Electrical Bio-impedance**:* Different types of tissue have different electrical properties due to variations in their cellular and molecular structure. Identification of tissue types at the needle tip based on the tissues' electrical properties is performed by measuring the electrical impedance, conductivity or permittivity of tissues as the needle tip contacts them [109].

The use of this technique has been investigated in different medical procedures. In ophthalmic anesthesia training, a multi-electrode electric field-based sensing system has been introduced where the precision for needle insertion into a confined intraorbital space can be enhanced [110]. Similarly, for intravenous procedures, EBI sensing technique has been investigated to perceive puncture status, ensuring accurate and safe needle placement such as intravenous process (Fig. 6(b)) [111], [112]. In the context of spinal procedures, a bipolar needle electrode-based EBI sensing has been employed in clinical lumbar punctures to detect spine structures, alerting the practitioner once the needle tip enters the narrow epidural space [113]. Study [114] introduced a method utilizing the micro electrical impedance spectroscopy-on-a-needle technique. By printing a selective passivation layer on a hypodermic needle, precise measurement of the electrical impedance of tissues was enabled. This technique allowed discrimination between different tissue types at varying depths during medical procedures.

In addition, the fact that cancerous tissue normally presents a higher electrical conductivity than normal tissue has inspired several applications. For instance, a needle electrode-based method for early prostate cancer detection by gauging the tissue's electrical properties has been proposed by [115]. The SmartProbe system has been developed as an EBI sensing device specifically for detecting head and neck cancer tissues, providing surgeons with a valuable office-based tool for early diagnosis [116].

Furthermore, study [117] discussed the combination of different types of bio-sensors, such as EBI, pH and glucose concentration, in a puncture detection task. Potential improvements in the detection of correct needle placement for the biopsy of suspicious tissues were reported.

B. Attached sensor

*1) **Force sensing**:* As an alternative to the above, the measurement of forces exerted on the needle can be achieved through FBGs or strain gauges attached to the needle shaft. In study [118], a silicon-based semiconductor strain gauge was attached to the thinning region of a biopsy needle. The study demonstrated that the interacting force at the needle tip could be measured accurately.

*2) **Acoustic sensing**:* An innovative approach was presented in [119], where an audio sensor (a stethoscope, Fig. 6(d)) was attached to the needle. This method capitalized on the distinct acoustic signatures of different tissues to detect needle perforation events. An extended study indicated the combination of audio stethoscope and force signal could further improve puncture detection accuracy [95].

C. Sensor on the hub

*1) **Force sensing**:* The insertion force sensing can also be measured through a force sensor on the syringe holder as shown in Fig. 6(e). This method was used in a robotic system built for lumbar puncture [120]. A similar technique was used in intravenous injections [121], where a drop in the axial force was observed at the moment of venipuncture. Regarding epidural injections, previous studies also proposed to integrate a force sensor over the syringe handle for measuring the the push force [122], [96], [123]. The change of the pushing force was successfully used to detect the access of the epidural region. Study [124] revealed that the measured force and torque at the needle base could be linked to the needle deflection, and eventually to the puncture detection. Also, study [125] demonstrated the feasibility of using rotation force sensing for detecting when the needle tip accessed the target tissue (i.e., tumor tissue in this case).

*2) **Blood flashback**:* For applications regarding vascular access, a straightforward method for puncture detection is the detection of blood flashback [126]. In this study, the detection system was realized through a 570 nm wavelength light emitting diode (LED), and a photodiode. The emitted light was transmitted through a transparent syringe onto the photodiode. When blood entered the syringe following a successful venipuncture by the needle, the presence of blood in the syringe body obstructed the light path, generating a trigger signal.

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TABLE I
EXISTING SENSING TECHNOLOGIES FOR GUIDING A NEEDLE PROCEDURE IN DIFFERENT MEDICAL APPLICATIONS. (N.R.: NOISE RESISTANCE; H: HIGH; M: MEDIUM; L: LOW.) (€: 1-10; €€: 10-100, €€€: 100-1000, AND €€€€: 1000-10000.)

Tracking	Implementation	Accuracy	Cost	Portability	Compatibility	N.R.	TRL	Medical application examples
Force	On-Hub	0.3-1.8 mm	€€€	H	H	L	6	Brachytherapy [124], [33]
EM	Embedded	< 2 mm	€€€	M	M	L	9	Tumor ablation [6], spinal puncture [8], [127], arterial puncture [9], local anaesthesia [128], brachytherapy [12], [129], eye anesthesia [10], biopsy [11], needle aspiration [130]
Strain gauge	Attached	<2 mm	€€+€	H	M	M	5	Biopsy [50], [49]
PZT	Embedded	0.14 mm	€€€	M	M	H	6	Local anaesthesia [16], [17], biopsy [131]
IMU	On-Hub	0.9-1.7 mm	€€	H	H	H	5	Intracranial hematoma [28], biopsy [29]
UWB	On-Hub	-	€€€	L	H	H	5	Biopsy [30]
FBG	Attached	< 0.5 mm	€€€€+€€€	M	M	M	6	Arterial puncture [36], lumbar puncture [37], ablation [41], epidural anesthesia [38], [122], nephrolithotomy [13], ablation [41], biopsy [39], brachytherapy [40], neurosurgery [132]
Photoacoustics	Embedded	0.7-2 mm	€€€€+€€€	M	L	H	5	Biopsy [133], [18], fetal surgery [15]
Electrical voltage	Embedded	<10 mm	€€	H	H	M	5	EMG [134]
Optic marker	Tracking	1-5 mm	€€€	L	L	M	8	Osteotomy [26], nerve stimulation [135], biopsy [22], Intramuscular injection [21], epidural [27]
US	Image-guided	-	-	M	H	H	7-9	Brachytherapy [53], [59], biopsy [136], local anaesthesia [55], [56]
Fluorescence	Image-guided	-	-	L	L	H	9	Biopsy [60], transjugular intrahepatic portosystemic shunt [62], percutaneous [61]
MRI	Image-guided	-	-	L	L	H	6-9	Biopsy [137], [138], intervention [65], [139]
Stereo-vision	On-Hub	3.3 mm	€€	M	H	L	5	Percutaneous [140]
Kinematics	On-Hub	1.3-1.5 mm	-	L	L	L	5	Biopsy [32]
Proximity	**Implementation**	**Accuracy**	**Cost**	**Portability**	**Compatibility**	**N.R.**	**TRL**	**Medical application examples**
Force	On-Hub	0.58 mm	€€	H	H	L	5	Epidural anesthesia [92], [141]
EM	Embedded	1.4-1.6 mm	€€€	M	M	L	6	Local anaesthesia [91]
EBI	Embedded	0.3-2 mm	€€+€	H	M	M	7	Neuro-monitoring [142], brainstem biopsy [82]
OCT	Embedded	0.04-3 mm	€€€€	M	L	H	8	Corneal [87], pneumoperitoneum [88], alveoli tracking [86], transbronchial aspiration [89]
PZT	Embedded	0.95 mm	€€	M	M	H	5	Lumbar puncture [80]
Laser Doppler	Embedded	0.3 mm	€€€€+€€	M	L	H	5	Neurosurgery [81]
Puncture	**Implementation**	**Accuracy**	**Cost**	**Portability**	**Compatibility**	**N.R.**	**TRL**	**Medical application examples**
Force	Embedded, Attached,	91%-97.1%	€€€	H	M	M	6-9	Epidural anesthesia [102], [123], [96], lumbar puncture [120]
	On-Hub	-	€€€	H	H	L	8	Biopsy [100], nerve block [104], [143], [103]
EBI	Embedded	75.5%-100%	€€+€	H	M	M	7	Cancer diagnosis [115], [116], lumbar puncture [113], venipuncture [112], [111]
Photoacoustics	Embedded	92%	€€€€+€€	M	L	H	5	Biopsy [144]
Stethoscope	Attached	78.7%-100%	€€€	H	M	H	5	Percutaneous [95], [119]
Blood flashback	On-Hub	100%	€€	H	H	H	6	Intravenous [126]
Optical Spectroscopy	Embedded	-	€€€	M	M	H	7	Biopsy [93]

V. Exploitation

A. Comparative analysis of methods

Table I categorizes the aforementioned sensing technologies used in needle-based interventions, detailing their medical applications, achievable accuracy levels, installation cost, portability, compatibility with the standard of care, noise resilience and Technology Readiness Level (TRL), divided into *(i) tracking*, *(ii) proximity*, and *(iii) puncture* by their purpose. The accuracy in tracking and proximity represents the normal position error of the sensing technology reported in the literature, while it gives the achievable success rate in puncture detection.

The cost metric considered in this table focuses on the sensor itself and its installation costs, excluding the medical device certification costs. The estimated cost is based on the data from 2023 and is presented in Euros (€). If the sensor device comprises both reusable and disposable components, the cost is represented by "the cost of the reusable part" plus "the cost of the disposable part".

The portability of the sensor technology is assessed in terms of its ease of transport and use in different locations. This evaluation takes into account not only the sensors on the needle but also the corresponding signal processor or analyzer, if any. Three levels of portability, namely high (H), medium (M) and low (L), have been assigned to indicate a one-piece device, a device plus a separate analyzer, and a grounded device, respectively. Compatibility here refers to the potential interference when integrating a sensing technology into current clinical practices. A score of high (H) indicates minimal changes required in the current clinical setup, medium (M) indicates the need for a custom needle, and low (L) indicates major modifications to the needle, environment, and routine practices. The noise resilience is evaluated based on the technology's ability to accurately acquire signals despite environmental perturbations. An "M" rating indicates that the noise can be effectively reduced through signal processing and filtering techniques, while an "L" indicates the need to physically avoid the noise source. Furthermore, the Technology Readiness Level (TRL) is used to indicate the maturity of the sensor technology, from concept (TRL1) to product deployment (TRL9).

As shown in Table I, the specifications of sensing technologies are summarized and compared. Medical imaging modalities such as US, fluorescence, and MRI are already deployed in daily healthcare and are considered standard. As fluorescence, CT and MRI are grounded machines, patients have to be transported to the imaging facility for operation. Similar disadvantages appear for technologies like UWB and optical markers, which require the use of markers. Moreover, most sensing technologies based on force sensor, strain gauge, IMU, electrical voltage, EBI, stethoscope, and blood flashback techniques, can be integrated directly with the needle as a single device. While methods based on EM, FBG, photoacoustics, US, stereo-vision, OCT, PZT, laser Doppler, and optical spectroscopy require an additional signal analyzer, which potentially reduces portability.

In terms of compatibility, most sensing technologies require modifications to the needles (e.g., EM, strain gauge, PZT, FBG, EBI, embedded & attached force sensors, stethoscope, and optical spectroscopy) or significant changes in current clinical settings (e.g., photoacoustics, optical marker, fluorescence, MRI, kinematics, OCT, and laser Doppler). However, some techniques allow minimal customization, for example in the cases of on-hub force sensor, IMU, UWB, electrical voltage, US, stereo-vision, and blood flashback).

According to publications, signal noise in methods based on force, kinematics, or stereo vision can be attributed to patient movement, while EM is highly sensitive to ferromagnetic materials in the sensing volume and susceptible to electrical noise. This kind of noise is generally hard to compensate for, and thus, a controlled environment is always needed. In addition, sensing methods based on strain gauge and FBG technique are temperature sensitive. EBI-related methods are sensitive to physiological bio-electric signals.In this case, signal filtering and multi-fiber installations are reported helpful [43], [145]. Generally, other sensing methods exhibit sufficient noise resilience capabilities.

High-precision applications, requiring sub-millimeter accuracy like corneal surgery, pneumoperitoneum, cancer treatment, lumbar puncture, and neurosurgery, are found often to utilize methods such as OCT, FBG, EBI, and PZT. These techniques are usually able to be integrated into a smaller size needle as mentioned above, although controlled environments may be required in some cases and the cost of some techniques may be relatively higher. For interventions like cancer biopsies, eye anesthesia, and brachytherapy, where accuracy ranging from 1 to a few millimeters suffices, popular choices include strain gauge needles, EM, or robotic kinematics, favored for their cost-effectiveness and ease of system integration. For less precision-critical procedures like general percutaneous needle injections and EMG electrode placement, external sensors like optic markers or stereo cameras attached to the needle are preferred, offering low cost in system setup.

In some cases, integrating multiple sensing modalities may be necessary to enhance efficacy and robustness. Sensor fusion combines the strengths of each sensor while compensating for their limitations, thus providing complementary benefits. For example:

- One sensing modality may be used for needle tracking, complemented by ultrasound imaging for tissue target tracking. In study [146], MR images identify the target location, while an FBG-based tracker monitors the needle tip position during insertion. Similarly, research by Seifabadi *et al.* uses CT imaging to localize tissue targets and ultrasound to guide the needle [147].
- Different modalities or medical imaging techniques are fused to improve needle-sensing robustness. In study [148], strain measurements from FBG sensors are utilized for online 3D reconstruction of the needle shape. These data are fused with 3D shapes obtained from US imaging, achieving an error below 1.5 mm. Another study proposes to combine injection pressure sensing and electrical sensing for confirming subparaneural placement and detecting intraneural access by the needle tip during a peripheral

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nerve block [143]. Improved accuracy is demonstrated. Another example shows a concept of fusing signals from an optical sensor at the needle base with those from an electromagnetic sensor on the needle tube for needle tip position estimation. An improved tracking error of 3.15 mm is reported [143].

B. Technology Readiness Level assessment

The selected sensor technologies in this review are all at or above TRL5, considering that their development should have already been characterized and verified as feasible for the intended medical application. Among them, medical imaging systems, such as US, CT and MRI, are at the highest TRL since they have been used in standard medical care for many years. Nevertheless, if artificial intelligence (AI) is involved in image processing, such as for needle segmentation, reconstruction, and tracking, the technology maturity level at the current stage is slightly lower (TRL7) [149], [150], [151], [55], [152]. Another two sensor modalities that are at a very high TRL are the EM and OCT-based technologies. These modalities have been investigated extensively for years, and NDI Inc. has the Aurora needle tracking system in the market since 2021. On-hub force sensing is characterized by its low cost, high portability, and compatibility, and has been integrated into some medical platforms like VenousPro (VascuLogic LLC), which has proceeded to clinical trials. Also, pressure monitoring sensor (CompuFlo, Milestone Scientific, US) has already been applied to clinical practise, specifically during peripheral nerve blocks [104].

Additionally, most techniques that require custom designed needles are still in the early stages (TRL5-6), such as techniques based on strain gauges, PZT, FBG, photoacoustics, electric voltage, laser Doppler, attached and embedded force sensors. It is anticipated that some of these technologies will advance to a higher TRL once the manufactured needles can pass safety tests, including bio-compatibility and sterility. Two special cases are techniques based on EBI and optical spectroscopy. Although needles with special functions are required, there are already similar certified medical needles in the market, namely concentric electrode needles and concentric optical needles. The existing market presence facilitates the validation process, allowing them to reach a higher TRL (TRL7) [116]. Otherwise, as is the case for the other reviewed technologies, the development phase is still addressing their feasibility against the medical requirements. Technologies based on attached or embedded force sensors, IMU, stereo-vision, and blood flashback detection are still at a relatively low TRL.

Another significant gap exists between TRL8 and TRL9, which involves obtaining medical device certification from regulatory authorities such as the U.S. Food and Drug Administration (FDA) or a European Competent Authority for medical devices. This process may take several years, and a higher class level is typically associated with a more extensive review process, leading to a longer processing time. Taking the European Medical Device Regulation (MDR) as an example, it is common to have separate MDR classification for the needle and the sensor device, if they can be divided and sold separately. If a customized needle is used solely for insertion assistance, it might be classified under Class I. However, if the needle incorporates specific sensing functions, it could be classified in a higher class depending on the associated risks. Depending on the intended use and the feedback provided, the sensor device can be classified from Class II.A to Class III. While the sensing system is crucial, the primary determinant for classification is the risk associated with the device, as well as whether it offers only monitoring functions or enables active intervention.

C. Signal Monitoring and User Interfaces

Moreover, the monitoring and interfacing of sensing information to enhance needle-based medical interventions can be categorized into three primary types. Real-time data from sensors can be: 1) Directly presented to the physician; 2) Integrated into an extended reality framework; 3) Integrated with robotic systems for autonomous or semi-autonomous operations. Each category is presented in details below.

1) ***Direct feedback****:* A straightforward way to provide information about the needle to clinicians is to display sensory data on a screen. Interesting examples include the integration of such information with the images provided by a US, or CT devices [153], [154]. This enables intuitive presentation of the sensed data with the real-time images of the anatomy, facilitating the work of the clinician in terms of optimizing the needle path and final placement, and thus potentially reducing the risk of inadvertent damage to adjacent structures.

To exploit a more natural hand-eye coordination, an alternative approach could be to provide feedback to clinicians directly on or around the operation site, which can avoid diverging the gaze of the physician from the patient to a screen. For example, an effective approach might be to convert the sensed information to an indication such as illuminating an LED or emitting an audio cue[155].

2) ***Extended reality****:* Extended Reality (XR) and Augmented Reality (AR) systems are potentially highly intuitive ways of providing visual guidance during medical procedures. Recently, different research groups proposed AR frameworks to provide needle tracking information for insertion aid [156], [157], [135]. For the implementation of such systems, the needle trajectory, position and orientation can be obtained using one of the sensor modalities described above. Then, this information is superimposed onto a real-time view of patient's anatomy [158]. For example, this has been investigated based on US [153], [129] and CT imaging systems [154]. XR and AR can simplify hand-eye coordination in imaging-guided needle insertions, facilitating needle alignment and guidance towards the target.

3) ***Robotic needle insertion****:* Recently, different robots have been developed to offer automated solutions for needle insertion procedures [159]. The sensing technologies can play important roles in the feedback control of robots, providing critical data regarding insertion tracking, target proximity and puncture detection. For instance, robots such as Haemobot [121] and VenousPro [160] have been developed to enable fully autonomous intravenous procedures. These systems incorporate a variety of sensing technologies, which are carefully selected and integrated throughout the needle insertion process.

Alternatively, human-robot cooperative needle insertion has also been explored. Examples include the MIRIAM system [139] and the CathBot device [111]. The MIRIAM system provides haptic feedback to the physician by amplifying the sensed insertion force, allowing them to control the insertion depth with the haptic device while the robot controls the needle orientation. Furthermore, an algorithm for pre-operative target localization is introduced to provide the robot with precise target coordinates. The CathBot device integrates an EBI sensor and a mechanism for automating the detection of venipuncture, delivering the catheter and retracting inner needle during a peripheral intravenous catheterization while the physician just needs to aim the device towards the target vessel and push the handle forward.

Additionally, image-guided needle insertion robots have been developed. For instance, Moreire *et al.* in [146] introduced a flexible needle steering system integrating an MRI compatible robot and a FBG-based needle tip tracker. MRI images located obstacles and targets, while FBG sensors provided strain data for real-time needle tip position estimation. This work achieved to combine MR imaging and FBG-based tracking for closed-loop needle steering inside an MR bore with an average targeting error of 2.76 mm.

VI. Outlook

This paper discusses different sensing technologies for assisting in medical needle insertion procedures, specifically for the purpose of needle tip tracking, target proximity sensing and puncture detection.

As the field of needle insertion guidance technology continues to evolve, several promising future directions are emerging that aim to enhance accuracy, reduce installation cost, increase portability, improve noise resilience, and compatibility with current clinical environments. Nevertheless, the selection or design of sensors should strike a balance among these factors according to the specific medical application. In many cases, the focus should be on meeting the necessary requirements and specifications rather than maximizing accuracy.

A key area of focus is the development of multi-modal sensing systems. These integrate various types of sensors to offer a more comprehensive and real-time understanding of needle position and tissue interactions. However, the integration of multiple sensors and complex algorithms can often result in bulky systems that are not easily transportable, limiting their applicability in different clinical settings. This points out an emergent need to create smaller and more robust sensors that can be seamlessly integrated into existing medical tools and robotic systems. Also, a higher level of sensor integration is necessary to ensure the miniaturization requirement, where Microelectromechanical Systems (MEMS) technology will play a crucial role.

The advancement of AI-based algorithms for sensor fusion is also anticipated, which will aid in real-time decision-making and potentially pave the way for more autonomous or semi-autonomous operations. In this context, corresponding advancements in robotic technologies are expected to complement these developments. However, the real-time processing of complex sensor data poses computational challenges that can impact the system's responsiveness and, consequently, its clinical utility. Therefore, light weight models will likely be preferable.

Additionally, ongoing research is targeting the development of new sensing techniques to overcome current challenges, such as high costs, fragility, and environmental sensitivity. One example is Acoustic Radiation Force Impulse (ARFI) imaging, which is a non-invasive approach to assess tissue stiffness [161]. Another promising direction for exploration is the use of electrochemical sensors, which can monitor biochemical changes or biomarkers in tissues, and potentially detect a puncture event.

Finally, research into user interfaces aims to provide physicians with a more intuitive and convenient operational experience, especially when dealing with complex sensor data. Future research may expand the use of XR to provide surgeons with enhanced visualization and interactive guidance during procedures.

While advancements in needle insertion guidance technology are promising, several open challenges remain that need to be addressed to fully realize its potential in terms of medical applications. One of the major challenges is to accurately guide an ultra-long, thin needle to a deep tissue target, as is often required in neurosurgery. This is an area where needle steering has been extensively researched [81]. As the needle is inserted deeper into the tissue, maintaining a high level of accuracy becomes increasingly difficult, considering the anatomy complexity and potential needle bending. Additionally, the challenge of needle trajectory planning and real-time needle tip localization in relation to the surrounding tissue complexity could be addressed by involving advanced simulation algorithms and imaging techniques.

Future studies in this domain should also put a higher emphasis on assistive technology for delicate patients such as infants and pediatrics [162]. This is because their smaller body size and intricate anatomical structures demand even greater precision and care. The integration of high-precision and miniaturized sensing technology could provide real-time feedback and enhanced guidance, thereby improving the safety and success rate of procedures on these patient populations.

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