Robotic Devices for Assisted and Autonomous Intravenous Access

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***Abstract*—Intravenous Access (IVA) is the most common invasive medical procedure. Globally, it is estimated that over one billion IVA devices (needles/catheters) are used annually. However, the overall failure rate in this procedure is unacceptably high, reaching values between 35 and 50%. This has driven a great deal of research and technological development over recent decades, including the integration of different levels of autonomy in IVA medical devices to greatly improve this process. This paper will review these recent technical developments, including methods and systems for vein imaging and localization, needle insertion, venipuncture detection, catheter placement, and complete robotic IVA platforms. Furthermore, this paper explores emerging technical aspects, current limitations, and new research directions that may enable wider clinical translation and better acceptance of robotic IVA technologies.**

***Index Terms*—Intravenous access (IVA), robot-assisted, peripheral catheterization, PIVC, autonomous medical procedure, vein-imaging.**

I. INTRODUCTION

GLOBALLY, intravenous Access (IVA) is one of the most common surgical procedures, with over 1 billion intravenous insertions annually [1]. Normally, IVA is performed for fluid injection, drug delivery and blood sampling on a peripheral vein, most commonly the basilic or cephalic vein of the lower forearm. The standard procedure involves inserting a needle and catheter/cannula into one of these peripheral vessels. This is known as Peripheral Intravenous Catheterization (PIVC), and involves inserting a soft catheter into the vein with the help of a needle, which is subsequently removed while the small catheter remains in place. Best practice involves finding a large and sufficiently straight vein to facilitate the insertion of the needle and delivery of the catheter. Difficult Intravenous Access (DIVA) occurs when the target veins are not easily accessible, as in pediatric patients and neonates, or when they are not visible because of any reason related to skin color, hair presence, high body fat, dehydration or lack of healthy veins. In such cases, IVA into deep-seated veins (subclavian, jugular, or femoral vessels) is an alternative emergency venous access route. This latter procedure, which directly accesses the large central veins near the heart is also known as Central Venous Access (CVA), and it is a key step in a variety of cardiovascular treatments, such as delivering drugs and treatments for cancer or infections.

Conventionally, intravenous procedures are performed freehand, however, a small number of assistive technologies are available to support the clinician. Nonetheless, the success of the procedure depends, to a large extent, on the experience and skill of the clinician and the physiology of the patient. This is reflected in the relatively low success rates of IVA operations reported in the literature, with values between 60% and 70% on average, although [2] reported success rates as high as 91% when the clinical staff is specialized in infusion therapy, or as low as 53% when such relevant expertise is absent. At the same time, multiple insertion attempts, can cause discomfort, pain and anxiety for both patients and clinicians. As a result, protocols from the Infusion Nurses Society stipulate that IVA should not be attempted more than twice by any nurse [3]. This is important because IVA problems can lead to severe complications, such as infiltration, hematoma, embolism or even thrombosis.

Analysis of IVA challenges focuses on the need to remove the critical dependence on the operator's experience. One way to achieve this involves using sensors and robotic technologies. Indeed, over the past two decades advanced robotic solutions and artificial intelligence (AI) approaches have gradually appeared in the IVA literature. In this paper, we review the state-of-the-art in robotic technologies that have been developed and tested to facilitate peripheral intravenous access, and support clinicians during all stages of the procedure. First, we briefly present the main steps in the intervention and describe their requirements. The key challenges of each step are highlighted, and computer-assisted solutions that have been proposed to address them are analyzed. Subsequently, robotic IVA devices are classified based on their level of autonomy. Finally, the current development status of the technologies and future research challenges are presented.

II. CRITICAL STEPS FOR ASSISTED AND AUTONOMOUS INTRAVENOUS ACCESS

Clinical procedures for intravenous access involve the following main steps:

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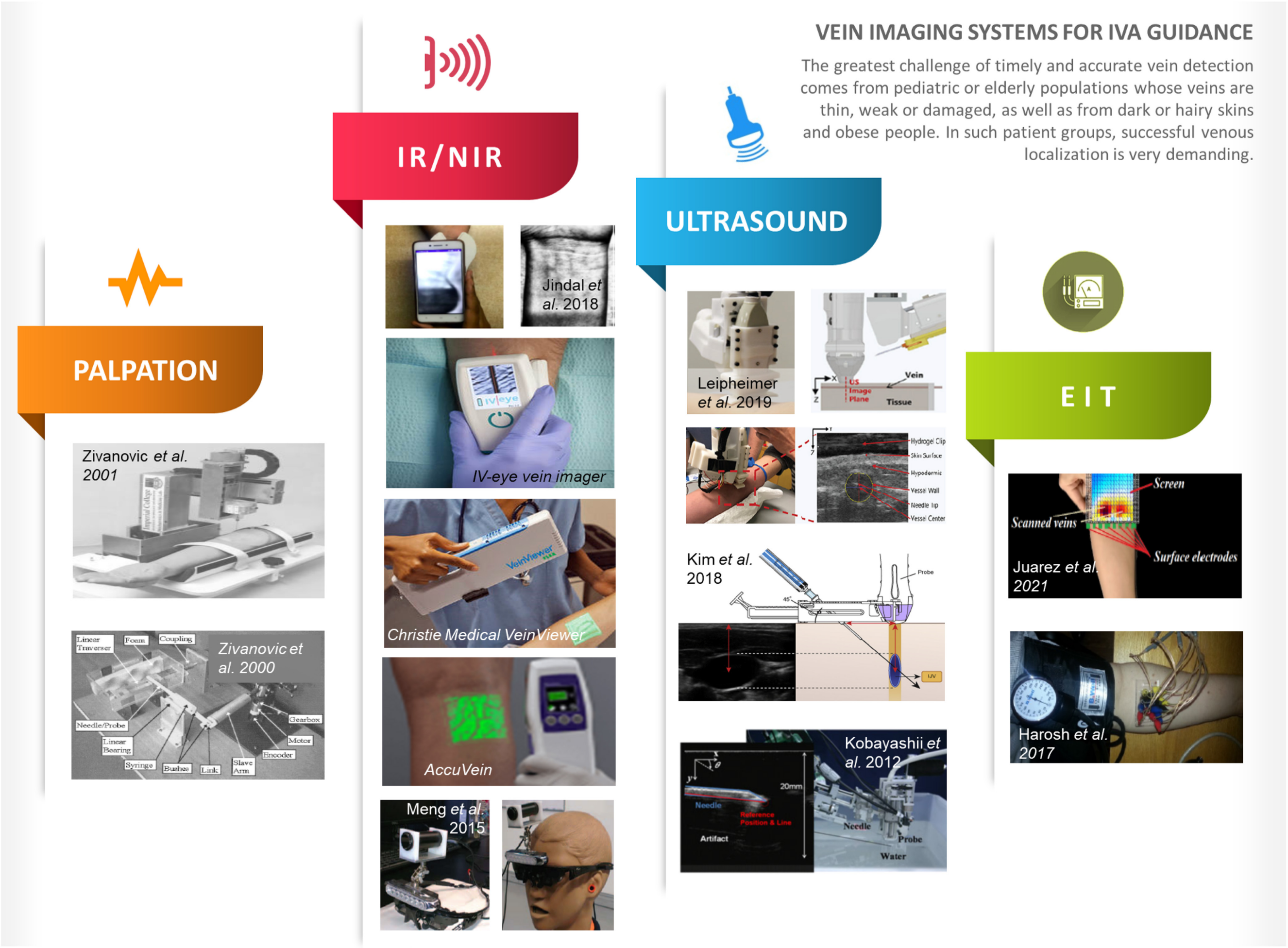

Fig. 1. Representative IVA systems enhanced with the most frequently used guidance technologies for vein-imaging, namely ultrasound, IR/NIR imaging, force, and EIT.

(i) *Vein perception and localization:* This first critical step requires appropriate hardware and dedicated software for accurate vein detection and localization.

(ii) *Venipunctute detection:* This involves a sensory setup and algorithms for robust venous entry detection, i.e., a system to detect when the needle enters the blood vessel.

(iii) *Needle insertion/retraction control:* This regulates motion control of the needle, which must be aligned and moved towards the target vessel until venipuncture is detected. Next, it should stay inside the vessel until the catheter which slides over the needle is delivered into the vessel. Finally, the insertion mechanism should retract the needle, completing the operation.

In the following sections, we discuss the requirements and challenges of these steps, and review the state-of-the-art technologies proposed to address them.

A. Perception: Vein Visualization and Localization

IVA involves vein selection before needle insertion. Clinicians select peripheral veins based on vein visibility or touch, and vein stimulation may be needed. This is typically done by adjusting the limb position or using tourniquets.

1) Challenges: Vein perception is particularly challenging in obese patients, in patients with dark or hairy skins, and in pediatric and elderly patients, whose veins are thin and delicate. In such patient groups, venous identification and localization is a demanding operation, leading to failure rates between 30 and 50% [4]. This can lead to multiple attempts until a successful IVA is achieved. The associated difficulties also increase the chances of extravasation, phlebitis, bruising, haemorrhages, catheter-associated infections, and sepsis, thus aggravating morbidity [5]. Failure during the vein perception usually requires an alternative solution such as central venous puncture, which increases the risks for the patient and the time/cost of the procedure [6].

2) Proposed Solutions: In recent decades, sensing technologies such as palpation, infrared (IR), near-infrared (NIR), ultrasound (US), and electrical impedance tomography (EIT) have been used to facilitate vessel localization. Figure 1 shows the most commonly used vein imaging systems for IVA guidance, and these include:

Palpation: Zivanovic and Davies [7] developed a manipulator that can visualize and identify the target vein by palpating the tissue surface in the area of interest. The applied force indicates the presence of the vein by highlighting the tissue characteristics against the background. An updated system, where the vein visualization is tested 14 times on a single arm, demonstrated an accuracy of 78% [8].

Infrared/Near-Infrared Imaging (IR and NIR): Infrared (IR) imaging systems can be used to capture vein patterns inside the human body [9]. IR and NIR light can penetrate through human tissues to a depth of about 3 mm. In addition, haemoglobin absorbs more IR light than the surrounding tissues, making veins appear as darker patterns in the IR images. This imaging method works well even in patients with small or "invisible" veins, such as those in the challenging populations mentioned above. Moreover, this imaging technology allows mapping the veins in 3D, e.g., using a stereo NIR camera system [10].

In 2012, Prabhu et al. [11] used two different approaches based on a NIR Web-camera at a distance of 14 cm, and a DSLR (Digital Single Lens Reflex) camera with an external filter to block visible light, to aid intravenous delivery of haemostatic agent. The experiments focused on visualization of veins in the palm with the DSLR images having better performance. In related research, Hu et al. in [12] described a binocular vision system based on two NIR CCD cameras and several 850 nm NIR LEDs to capture IR images of the hand. They used the stereo vision to recover the hand's 3D structure. Additionally, VeinLoc by Agarwal and Vidhya [13] used a similar NIR imaging system for blood vessel detection and localization.

In contrast, Meng et al. [14] developed a prototype of a wearable vein localization system using NIR imaging. Specifically, they used the Vuzix STAR 1200XL eye wear system as a headset device on which they mounted an IR CCD camera with NIR LEDs. However, this head-mounted device was large, heavy and impractical for the clinicians. Moreover, Qu et al. in [15] designed an app. for smart phones to transmit and process the captured image from a NIR camera. The study aimed to create a low-cost, accurate vein-imaging method, however, it was not completed, with the authors highlighting uncertainties that may occur during the image projection.

NIR imaging technology is also widely and successfully used in most commercial vein viewer products, such as the VeinViewer by Christie Medical Holdings Inc., the IV-eye Portable Vein Imager by CorVascular LLC, and the AV500 Vein Viewing System by AccuVein.

Ultrasound (US): Ultrasound machines are mainly used in challenging IVA cases to assist the manual operation. Clinicians typically use 2D US when vision and palpation fail, as it works across all skin types, gives a precise depth estimation, disambiguates between veins and arteries/nerves, and helps to align the needle with the vein [16]. However, 2D US images cannot show the IV needle with respect to the vein, until the tip penetrates the 2D imaging plane. Hence, US is often used as an auxiliary sensing technology to confirm the proper insertion location, while NIR imaging is used for pre-insertion vein detection and real-time guidance.

Several studies have examined the use of machine learning approaches to enhance vein visualization by detecting and highlighting peripheral and deep veins in US images [17], [18]. VeniBot [19] is a portable robotic system for autonomous venipuncture that uses a semi-supervised vein segmentation scheme from ultrasound images for autonomous navigation and guidance. VeeBot [20] is a robotic system based on an EPSON robot, that has been customized for intravenous access and uses NIR imaging as the primary vein-detection method, and ultrasound to confirm the target vein has adequate blood flow. VeeBot has achieved a 83% vein identification success rate. For the injection phase, VeeBot relies on the ultrasound's depth measurement to insert the needle towards the vein using a position control system. Similarly, Balter et al. [21] and Chen et al. [22] used the same sensing combination to ensure vein visualization and control the needle insertion.

Improved simultaneous visualization of the vein and needle tip can be achieved with 3D US systems. Further, Doppler ultrasound can facilitate vein detection and localization by providing information on fluid velocities in the probe's field of view [23]. This was described in the Smart Needle patent from 1989 [24], which used Doppler US for primary vein detection. More recently, Doppler US has been used as an auxiliary method to ensure vein detection [25], [26].

Electrical Impedance Tomography (EIT): EIT detects veins by sensing the electrical impedance of tissues. Compared to the other sensing modalities, EIT is relatively low cost, however, due to its diffused sensing characteristics, it is challenging to use EIT to obtain precise vessel contours. Nonetheless, a multi-channel electrical bio-impedance sensing system with surface electrodes was proposed for peripheral vessel detection in [27]. According to their findings, a lower impedance was recorded close to veins, with an identification accuracy of 1.75 mm. In [28], EIT reconstruction of a venous region was performed on a pig model, demonstrating the potential for *in-vivo* detection of vessels. San-Pablo-Juarez and Orozco-Corona [29] also investigated this, but in this case only in simulation.

B. Needle Insertion & Venipuncture

During needle insertion, the needle tip penetrates different tissue layers including; the epidermis, dermis, fat and vein wall. For deep IV insertion, the tip also pierces through a thin muscle layer that surrounds the vessel. In conventional operations, venous puncture is perceived as a small resistive force on the needle or by observing blood flashback in the needle hub. Immediately after the needle tip punctures the vessel wall insertion should be stopped.

1) Challenges: The detection of venipuncture is difficult since there is very limited sensory data. This frequently leads to IV insertion failures, with the most common causes being:

- *Missed vessel:* As shown in Fig. 2a, when the needle is pushed towards the vessel, the surrounding soft tissue can deform and displace the vessel, resulting in missing the vessel;
- *Shallow puncture:* The needle insertion stops before it enters the vessel (Fig. 2b);
- *Double puncture:* The needle tip passes through the vessel, exiting into the tissue beyond (Fig. 2c).

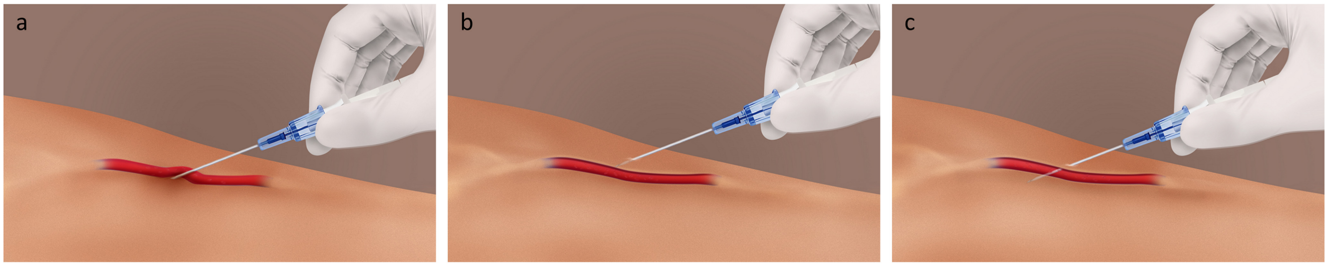

Fig. 2. Most common IV insertion failures causes: (a) off shot insertion; (b) shallow puncture; (c) double puncture.

Such errors should be detected as soon as possible, and corrective action (adjustment or retraction) taken immediately. Accordingly, reliable, timely and accurate signal sensing is fundamental.

2) Proposed Solutions: The use of sensing technology to assist with venipuncture can significantly increase the success rate. Recently, different sensing technologies have been investigated and developed including:

Ultrasound: As mentioned above, US imaging is popular not only for vein detection but also for needle guidance and insertion into a vessel, particularly during deep intravenous access. Views in the longitudinal and transverse direction are typically needed and explored by clinicians during the insertion process. This aims to detect both the blood vessel and the needle tip in the images [30]. Automatically detecting and tracking a needle tip in US images is an active research topic involving advanced AI techniques [31]. At the same time, US probes are relatively large, making embedding them in handheld devices difficult.

Blood pressure: Another possible venous entry detection method is based on pressure sensing through the needle hole [32]. Blood pressure is normally higher than 60 mmHg in arteries, and between 8 and 10 mmHg in most named veins [33]. Therefore, it is possible to detect when the needle tip enters a blood vessel by monitoring the pressure inside the needle. This approach is used in the Venous Entry Indicator Device (VEID) [34], which was assessed in a clinical study in 2008 [32]. Overall, blood pressure sensing technology is compact, has good compatibility with standard IVA needles, and is low cost. While, only technical concern is its sensitivity [34].

Optical spectral sensing: Alternatively, venous entry sensing can be based on the detection of blood, which has significantly different physical properties compared to the surrounding tissues. Study [35] reported using a needle with an optic fiber in the lumen, which connects to a bright green light source. The light absorbance of deoxyhaemoglobin (deoxygenated blood in veins) and oxyhaemoglobin (oxygenated blood in arteries) is peaked at ∼550 nm (green). Therefore, the light exiting the needle tip is observed dimmed when it enters a blood vessel. This optical sensing approach may also be able to recognize entry into a vein or artery by using a light source of ∼1450 nm, which is critical in deep vessel insertion.

Electrical Bio-Impedance (EBI): Since blood is more electrically conductive than surrounding tissues, researchers have investigated different venipuncture detection methods based on EBI. In 2006, Saito et al. [36] developed a venipuncture detection method based on a monopolar needle electrode. This approach registers a significant increase in conductivity when the needle enters the blood vessel. However, monopolar sensing is sensitive to the needle-tissue contact area. In an alternative approach based on bipolar sensing, developed by Cheng et al. [37] the sensor used a concentric electrode needle, which provides a robust local assessment of bioimpedance in the immediate vicinity of the needle tip. This has a mean overshoot of 817.6 μm after venipuncture and is deemed safe even for IVA on young patients. Both EBI and optical sensing techniques have been shown to provide good sensitivity, fast response and to have compact designs. However, both techniques require customized needles. In addition, these technologies may register to false readings in deep IVA due to contact with blood from peripheral capillaries before penetrating the target vessel.

Insertion force: Intuitively, puncturing of the vessel wall can be achieved by sensing the force acting axially on the needle. In 2000, when developing BloodBot, Zivanovic and Davies first investigated the use of force sensing in the needle insertion control loop [7]. The injection force signature against displacement has been analyzed, with the force peak occurring when the needle tip pushes and penetrates the vein wall. This is because the vessel wall is stiffer than the surrounding fatty tissue. According to [38], the forces on the needle can be divided to three components: cutting, friction and deformation. For venipuncture detection the cutting force is the most helpful [39], although other components may yield other useful information such as tissue deformation or needle bending. Nevertheless, forces on the needle are generally noisy with multiple peaks and drops associated with the puncture of the skin and friction. Needle insertion speed is an additional influencing factor, since soft tissue is a viscoelastic material [40]. These challenges indicate that using force sensing for robotic needle insertion control requires a controlled environment, with negligible unintended patient motions. Among venous entry detection methods force sensing is the most common, as it is intuitive and relatively low cost. In addition, it can work with standard IVA needles, however its reliability is not optimal.

C. Mechanisms for Needle Orientation and Insertion

Needle insertion control is another critical component in successful IV operations. Fully autonomous robots should integrate mechanisms of at least 5 DOFs: 3 translation (x, y,

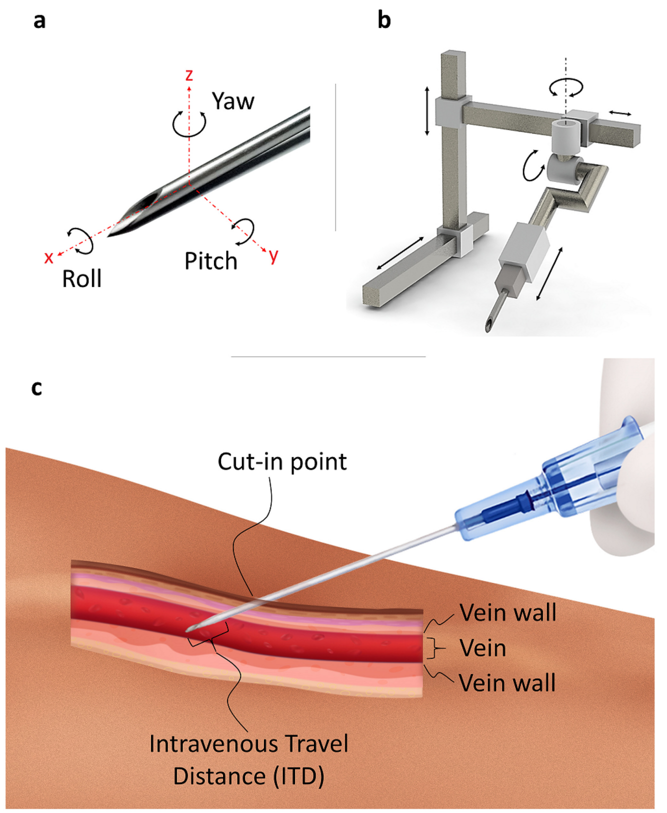

Fig. 3. (a) The control of needle insertion requires at least five DOFs including three translational components (x, y and z), and two rotational components (yaw and pitch); (b) A common mechanism DOFs arrangement for an autonomous IVA robot, while different mechanisms can be applied to achieve the same goal in practice; (c) The ITD refers to the distance from the needle tip to the vein wall.

and z) and 2 rotation (yaw and pitch), Fig. 3a. Potentially, redundancy is required to facilitate motion control and improve accuracy. Generally, rolling of a needle is not considered and the bevel direction is fixed facing upwards. For semi-autonomous robots, mechanisms are designed according to the target task, with fewer DOFs being needed.

1) Challenges: In addition to the multiple DOFs needed, the mechanism design should consider other parameters such as work space, load carrying capability, position accuracy, and stiffness needed to withstand the forces during needle insertion. Moreover, control of the needle tilt may be required from a relatively large 30° angle to a relatively small 10° angle during the insertion procedure. Since the insertion needle may also bend and the surrounding soft tissue can deform, adjustments are needed to ensure the insertion is towards the target vessel. This can be difficult with an autonomous robot since it involves delicate motion control.

2) Proposed Solutions: IVA mechanisms must balance functionality, maneuverability, and portability. Different applications require different DOFs, and this determines the complexity of the integrated mechanisms. Grounded robots often have more complicated and advanced mechanisms while handheld systems have fewer DOFs to enhance portability and human integration in the control loop. The IVA process involves two procedures. First, the needle is placed above, and aligned with, a target vessel; second, the needle is inserted into the vessel and advanced until it punctures the vessel wall. We call these procedures: carrier and end-effector respectively.

Carrier: This action positions the end-effector above the operating site with the needle pointing to and aligning along the target vessel. In laboratory setups, [20], [41], an industrial robot may act as the carrier. For practical systems, dedicated mechanical structures are integrated, e.g., a gantry structure was designed for BloodBot. This latter design had 4 DOFs (PRPP), with yaw motion being excluded [8]. The needle pitch joint was in the base and was controlled manually. For more complete insertion motion control, a 6 DOFs PPPRRP structure, as used in [42] and [43], is commonly selected as shown in Fig. 3b. Moreover, a redundant pitch DOF at the end was suggested for convenience in needle placement control by [25].

Other technical specifications for carrier requires a common motion precision of 0.2 mm and ability to support the end-effector weight and insertion force (typically <5 N).

End-effector: The needle insertion action could be realized by the carrier mechanism, however, for accuracy and safety, a dedicated design is often preferred. Based on this classification handheld robotic devices can be viewed as end-effectors since the clinician performs the carrier function.

IVA end-effectors generally have two DOFs: one prismatic DOF to push the needle forwards axially, and another pitch DOF for needle tilt control. Critical technical specifications include workspace, insertion speed, and force magnitude. The trajectory of needle insertion is bounded in a workspace of 21×5×5 mm. The overall axial displacement can be about 16 mm according to [43]. Another critical parameter is the motor step resolution which determines the overshoot distance, i.e., the distance between the needle tip and the cut-in point of the first vessel wall as shown in Fig. 3c. A high resolution linear actuator with micro-stepping or submicro stepping is used. Speed is normally higher than the manual operation (<5 mm/s), ranging from 10 to 60 mm/s [42]. Usually, a separate linear actuator is used to advance the needle. The insertion force during IVA is associated with multiple factors including needle size, insertion speed, patient's clinical history, age and gender. For insertion into a peripheral vein, the reported force ranges from 0.23 N to 3.9 N [44], [45]. For deep vein insertion, Kobayashi et al. reported a max of 3.8 N on a pig central vein when an 18G needle and 3 mm/s insertion speed was used [46].

Most robotic IVA systems execute a linear insertion trajectory [20], [25]. However, infusion nursing standards suggest using a higher tilt angle for piercing the skin and a lower angle for advancing the needle into the vein [3]. For peripheral IVA procedures, the tilt motion control should be about a remote center of motion (RCM) ideally located at the vessels' cut-in point, as indicated in Fig. 3c.

Other end-effector designs attempt to integrate mechanisms for stopping needle advancement immediately after venipuncture [47]. This is particularly effective in handheld devices, where needle forward motion is controlled manually. For instance, SDOP uses a mechanical latch to engage and disengage the handle and needle insertion mechanism [48]. This automatically stops the needle advancement once an on-board EBI sensor detects the accurate venipuncture site. In their

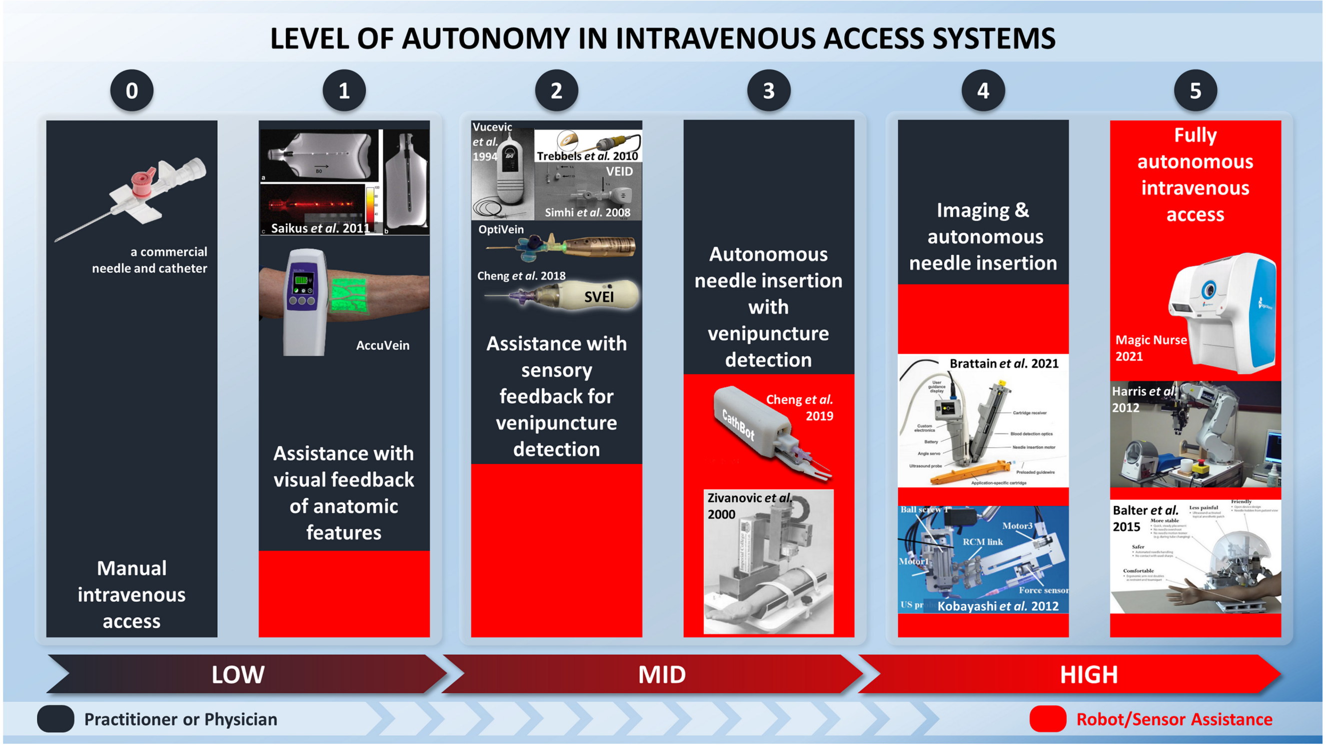

Fig. 4. Autonomy levels of IVA systems.

subsequent CathBot design, the authors proposed a crank-slider mechanism to simultaneously achieve needle retraction and catheter advance after venous entry [49].

III. Robot Autonomy Levels

Yang et al. in [50] suggest that medical robotic devices can be classified into six major classes based on their level of autonomy, with the involvement and complexity increasing as the autonomy level increases. In this paper, we follow a similar approach for classification of IVA systems (Fig. 4). We define *Level 0* as the traditional manual IVA without any help from a robotic or sensory system, and *Level 5* as the maximum autonomy level where no involvement of a clinician is needed. In the latter case, the IVA procedure is performed autonomously by a robotic system capable of vein detection and localization, needle alignment, needle insertion, venipuncture detection, catheter placement (if needed) and needle retraction.

A. Low Level Autonomy

Level 0 - Manual operation: This lowest autonomy level does not include any sensory feedback or robotic assistance. It follows traditional manual intravenous access, with the clinician being fully responsible the procedure. Actions include: (i) needle size and catheter type selection according to patient profile and the application, (ii) insertion site selection, (iii) preparation and sterilization of the insertion site, (iv) the complete IVA procedure, from vein selection to needle retraction, (v) catheter fixation and dressing placement.

Level 1 - Assistance with visual feedback of anatomic features: This level includes assistive systems that provide visual feedback on anatomical features such as veins. At this level, the systems do not provide any further sensory feedback or actuation assistance, with the clinician performing the IVA manually according to the traditional method. Different imaging and visualization systems are part of this group. For example, Prabhu et al. demonstrated an IR guidance system for vein localization [11]. Kopac et al. [51] presented usability experiments with the SonixGPS device by Ultrasonix Medical Corp., Canada. They performed needle insertion experiments on a phantom under guidance of traditional ultrasound and SonixGPS with 30 students from a medical department. All the students preferred to use the SonixGPS guidance rather than traditional ultrasound. Hu et al. [12] used a stereo IR vision system to get a 3D reconstruction of veins prior to venipuncture. Finally, Meng et al. [14] developed a head mounted display for IR image guidance, with a wearable device to assist the intravenous catheterization. These systems help clinicians by providing augmented visualization of veins/vessels, which increases the success rate of IVA procedures.

B. Mid Level Autonomy

These systems provide assistance only during specific steps of an IVA procedure, such as venipuncture detection. Therefore, a clinician is always involved in the operation. Advantages include lower cost and easier certification compared to systems with higher autonomy. Additionally, they may be more accepted by both clinicians and patients since the clinician is involved in the IVA procedure. On the other hand, there is the possibility of human error and the need for clinician training. Systems in this category can be grouped according to the complexity of the task they support.

Level 2 - Assistance with sensory feedback for veinpuncture detection: Detecting venipuncture is a challenging problem in IVA. Consequently, several devices have been developed to provide assistance. Systems in Level 2 only provide sensory feedback to the clinician. This may include, bioimpedance, force or pressure data. This information provides guidance to the clinician during the needle insertion process, contributing towards a successful IVA. The responsibility for the entire procedure is still with the clinician, who is better informed about the state of the operation with respect to the standard manual operation. Examples of devices in this group are SMART needles [52], VEID [32], and SVEI [53], which are all handheld devices that facilitate venipuncture detection.

Level 3 - Autonomous needle insertion: These systems are integrated with robotic mechanisms to autonomously accomplish subtasks of the IVA procedure. Sensory information (e.g., from a camera, force, pressure or EBI sensor) is used in the robot's control loop. At this level, the systems can make autonomous decisions while performing their sub-tasks. These include needle insertion control and/or needle stopping after venipuncture. Nonetheless, a clinician is still involved in the procedures, performing the remaining steps of the IVA procedure. Bloodbot [7], the Saito and Togawa system [36], and Cathbot [49] are included in this autonomy level.

C. High Level Autonomy

Robotic systems with *high level autonomy* (Level 4 and 5) use advanced sensing techniques and mechanisms to provide a completely autonomous IVA operation, with a clinician simply supervising the procedure. Furthermore, these robots typically integrate multiple functional subsystems of the IVA procedure, including preparatory tasks such as tissue disinfection.

The potential advantages of these systems include enhanced IVA efficiency and success rate. They minimize clinician involvement in the procedure, enabling savings in personnel costs and reducing human errors. Potentially, they may also decrease procedure time and eliminate infections. However, these systems are generally desktop devices with bulky and heavy structures, and, their high cost can create a barrier to widespread use.

Level 4 - Imaging & autonomous needle insertion: At this level, systems make decisions not only regarding venipuncture detection and needle stopping, but also selection of the IVA site. The systems presented by den Boer et al. [54] for peripheral venipuncture and by Kobayashi et al. [41] for central venous catheterization are typical examples in this autonomy level. The clinician is still involved in the procedure, however, with minimal contribution to decision making process, such as approving/cancelling the proposed actions. Other clinician tasks can include site preparation, holding the robotic system, and urgent intervention during an adverse event.

Level 5 - Fully autonomous intravenous access: The highest autonomy level involves robotic systems that can perform IVA fully autonomously, with no/minimal clinician involvement. These systems have perception and actuation mechanisms to successfully perform the individual tasks including: (i) vein imaging, (ii) selection of the needle entry site, (iii) sanitizing the site, (iv) needle insertion, v) venipuncture detection, (vi) subsequent medical operations such as catheter placement, (vii) injecting liquid or drawing blood from the vein. VeeBot [20], VenousPro [21], [22], [25], and MagicNurse [55] can perform fully autonomous IVA.

IV. OUTLOOK

Different levels of autonomy in IVA robots are often the result of balancing factors such as task difficulty for the clinician, availability of technical solutions, cost effectiveness, risks and the consequences of potential failures. Broadly speaking, there are those who are favor of keeping control in the hands of the surgeon, due to concerns regarding safety and legal responsibility. For others, robots can perform more precise, delicate tasks than humans, and AI is enabling them to take active roles in decision making during surgical operations. Hence, autonomous robotic surgical intervention can be potentially safer than direct manual operation, as demonstrated for surgical robots by Weber et al. [72].

Table I summarizes and classifies the technologies for intravenous access reviewed in this paper based on their level of autonomy and portability, i.e., (i) *grounded*: for the systems that can be hardly moved, (ii) *portable*: for those that can be easily moved and carried but placed static during use, and (iii) *handheld*: for devices that can be carried and used in the hand. In addition, publication year, keywords, application area, vein-imaging technology, feedback signals and Technology Readiness Level (TRL) are also provided. TRL provides a common definition for the development stage of a technology, from basic research to actual systems validated on patients. In the table, the TRL classification defined by the European Commission Decision C(2019)4575 is used.

From the table, it can be noted that higher autonomy levels correlate with reduced portability, as more sensors, actuators and mechanisms are common in higher levels of autonomy, making the system more complex and less portable. In addition, the needs of the target patients also play a central role. Current IVA robots with high autonomy have been designed for specific insertion sites, typically the elbow or the back of the hand, as it is technically challenging to achieve both autonomy and versatility on multiple sites. Handheld robotic devices, in contrast, typically provide a higher flexibility in terms of operation site, but at the expense of reduced autonomy.

Despite the huge number of IVA procedures performed daily, robotic systems that can assist in these tasks are still rarely available in hospitals and clinics. From Table I, it is evident that only assistive devices have reached clinical use so far (TRL 8-9). Except of MagicNurce, which was approved by China's National Medical Products Administration (NMPA) in 2019, the other fully autonomous IVA systems are still under investigation, with the most advanced devices currently undergoing clinical trials (TRL 6-7). Clearly, considerable testing and development is needed before fully autonomous IVA becomes common practice. Nonetheless, robotic technologies and AI-based assistive systems are starting to demonstrate the benefits they can bring to IVA.

TABLE I
SUMMARY OF TECHNOLOGIES AND ROBOTIC SYSTEMS FOR INTRAVENOUS ACCESS

Autonomy					Application		Sensing		
Level	Type	Study	Year	Keywords	Guide	VP	Technologies	Output	TRL
Low	Grounded	Prabhu *et al.* [11]	2012	IR, DSLR	●		IR, WebCam	Display	1-3
		Saikus *et al.* [56]	2011	MRI active needle	●	●	EM	CU	4-5
		Kopac *et al.* [51]	2013	SonixGPS	●	●	US, EM	Display	4-5
		Hu *et al.* [12]	2013	Vein-Imaging system	●		IR	Display	4-5
		Qu *et al.* [15]	2019	SmartPhones	●		IR	Projection, AR	6-7
	Handheld	Meng *et al.* [14]	2015	Vuzix STAR	●		IR	Display, AR	1-3
		Agarwal *et al.* [13]	2015	VeinLoc	●		IR	LED	1-3
		Trebbels *et al.* [57]	2012	Impedance spectroscopy		●	EBI	CU	4-5
		Jindal *et al.* [58]	2018	Mobile App	●		IR	Display	4-5
		Ahmed *et al.* [59]	2018	Mobile App	●		IR	Display	4-5
		Simhi *et al.* [32]	2008	VEID		●	Pressure	Sound	6-7
		Auyong *et al.* [60]	2015	eZono	●	●	US, EM	Display	6-7
		Kaneko *et al.* [61]	2016	HMD Moverio	●		US	Display	6-7
		Cheng *et al.* [53]	2018	IIT-SVEI		●	EBI	LED	6-7
		Kim *et al.* [62]	2018	AMO life Science	●	●	US	Display	6-7
		Chew *et al.* [63]	2020	eZono	●	●	US, EM	Display	6-7
		Kim *et al.* [64]	2001	VeinViewer	●		IR	Projection, AR	8-9
		Optivein [35]	2015	Optic fiber catheter	●		Visible laser	Green light	8-9
		Shaw *et al.* [65]	2017	IV-eye (Novarix)	●		IR	Display	8-9
		Demir *et al.* [66]	2019	AccuVein	●		IR	Projection, AR	8-9
Mid	Grounded	Ameri *et al.* [23]	2015	SonixGPS-like	●	●	US	Display	1-3
		Zivanovic *et al.* [7]	2000	BloodBot	●	●	Force	CU	4-5
		Saito *et al.* [36]	2005	Puncture force		●	Force, EBI	CU	4-5
		Kobayashi *et al.* [46]	2014	CVA	●	●	US, Force	Display	6-7
	Portable	Boer *et al.* [54]	2007	Saddle	●	●	US, Force	Display	4-5
	Handheld	Hebrew et al. [67]	2013	SAGIV	●	●	IR	Mini display, CU	1-3
		Cheng *et al.* [49]	2019	IIT-CathBot		●	EBI	CU	4-5
		Cheng *et al.* [68]	2017	SAID		●	EBI	LED, CU	6-7
		Cheng *et al.* [48]	2018	SDOP		●	EBI	LED, CU	6-7
		Leipheimer, *et al.* [45]	2019	Rutgers, First in human	●	●	US, Force	Display	6-7
		Xact Medical [69]	2019	FIND	●	●	US	Display	8-9
High	Grounded	Li *et al.* [70]	2019	Nyrio robot	●	●	IR	Display, CU	4-5
		Harris et al. [20]	2012	VeeBot	●	●	US, IR, Force	Display, CU	6-7
		Brewer [43]	2015	HaemoBot		●	Force	CU	6-7
		Ahmed *et al.* [71]	2017	AID	●	●	IR	Display	6-7
		Baltar, Chen *et al.* [25] [21]	2015	VenousPro	●	●	US, IR, Force	Display, CU	6-7
		MagicNurse [55]	2021	NMPA approved	●	●	US, IR	CU	8-9
	Portable	Cao *et al.* [19]	2021	Venibot	●	●	US	CU	4-5
	Handheld	Brattain *et al.* [18]	2021	AI-GUIDE, CVA	●	●	US	Mini display	6-7

* VP: Venipuncture, IR: (Near) Infrared, US: Ultrasound, CU: Control Unit, EBI: Electrical Bio-Impedance, EM:Electromagnetic, AR: Augmented Reality, CVA: Central venous access

Hence, it seems rather straightforward to opt for advanced technological solutions to improve IVA, including fully autonomous robotic solutions that do not require professional assistance. These technologies can potentially save time and resources for hospitals, and minimize pain, discomfort and side effects for patients. Looking towards the future, it is possible to envision IVA solutions that would allow self-care procedures at home, e.g., for blood collection for analysis. This would save significant amounts of healthcare resources, as dedicated facilities and clinical personnel would no longer be required for these very common procedures. Finally, it is clear that autonomous IVA systems can provide wide support during healthcare crisis like the recent COVID-19 pandemic, bringing relief to overstretched health systems and medical staff.

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