Automation, Surgery Support and Intuitive 3D visualization
to optimize workflow in image guided therapy SysTems

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State-of-the-art in the Field of Image-guided Robotic Systems

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- **Due date:** deliverable owner sends the final version of the deliverable to PM and co-reviewer

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1 Executive summary

This report is the first deliverable of work package 4 for the ASSIST Project. It begins with introducing its objective and the contributors that took part in it. Then, it is divided into three main chapters that explore the main topics of the work package from three different angles; medical, technical, and business. The first topic undertakes the state-of-the-art of the current robotic and navigation technology being used particularly in the liver oncology field. Moreover, it explores potential clinical applications for liver oncology. The second topic gives at the beginning a general overview of the technical aspects of navigation technology, then it particularly looks into the state-of-the-art of motion compensation. Finally, the last topic introduces the different types of feedback given to the physician in a surgical cockpit during robot-assisted interventions. It focuses on visual feedback, mixed reality, and haptic feedback as the main actors to provide an immersive experience. Each of the three chapters ends with a discussion to conclude the main outcomes taking into consideration the business aspects.

2 Glossary

AI	Artificial Intelligence
AR	Augmented Reality
CT	Computed Tomography
CCD	Charge-Coupled Device
EEG	Electroencephalogram
EM	Electromagnetic
FPI	Fabry-Perot Interferometer
HCC	Hepatocellular Carcinoma
HRV	Heart Rate Variability
IGI	Image-Guided Intervention
IMU	Inertial Measurement Unit
IR	Infrared
MIS	Minimally Invasive Surgery
MRI	Magnetic Resonance Imaging
RAS	Robotic Assisted Surgery
PET	Positron Emission Tomography
PLB	Percutaneous Lung Biopsy
RLR	Robotic Liver Resection
RMS	Root Mean Square
SPECT	Single-photon Emission Computed Tomography
US	Ultrasound

3 Introduction

3.1 Aim of activity

The aim of this report is to describe the state-of-the-art in the field of image-guided robotic systems. This report focuses on the technology that can be suitable for the ASSIST project and the planned clinical cases.

This work package aims to address minimally invasive clinical challenges integrating Artificial Intelligence (AI) and robotic control-based algorithms. These challenges include the compensation for organ motion that happens during patient's respiration process. The main objective of this work package consists in developing a surgical cockpit for the clinician with visual and haptic feedback to perform complex procedures with high precision and safety while accounting for the dynamic behavior of the human body. The developed surgical cockpit is expected to give more information and comfort to the surgeon and minimize the chances of human errors that can lead to damaging critical tissues with the interventional tools. Additionally, the work package aims to integrate the surgical robotics systems with existing imaging modalities.

This document is organized to discuss the current state of robotics in minimally invasive surgery, especially in liver oncology, followed by the navigation technology and surgical cockpit and state-of-the-art feedback systems. The analysis of these three areas will enable to comprehend the current needs and limitations to integrate a centralized unit of information to enable higher precision, coordination, and workflow optimization during complex clinical cases.

3.2 Contributors

Several authors contributed to the development of this document. Each of those authors was responsible for business (Philips Medical Systems Nederland B.V.), clinical (LUMC) and technical (University of Twente) contribution. An overview is shown in Table 1.

#	*Section*	*Authors*
1	Clinical Procedures Using Medical Robotics And Navigation For Liver Oncology	*UT, LUMC*
2	Technical Aspects: Navigation	*UT, LUMC, PMS*
3	Surgical Cockpit: Types of feedback	*UT, PMS*
	Global editor	*UT*

Table 1. Contribution of every author to this report

4 Clinical procedures using medical robotics and navigation for liver oncology

4.1 Introduction

The World Health Organization claims that cancer is a leading cause of death worldwide. In 2020, the number of cancer-related deaths accounted for approximately 9.5 million cases [1]. Lung and liver cancer were evaluated as the most common types of cancer that cause death. The former contributes the most to the number of deaths and the latter comes in the third place. Early diagnosis and effective treatment increase the chances of survival significantly.

According to the National Health Service in England, liver cancer can be diagnosed through imaging modalities such as CT, MRI, or ultrasound shown in figure 4.1 . Blood tests and biopsies are also crucial means of detecting liver tumors [2]. Additionally, it can be treated through surgery, chemotherapy, thermal ablation, targeted medicines, and radiotherapy [2]. Accurate targeting of the lesion is essential to reduce the possibilities of misdiagnosis, incomplete treatment, or unintended destruction of healthy tissues [3]. In radiotherapy, inaccurate targeting might lead to cancer relapse since the tumor might have received an insufficient dose or the dose might have affected healthy tissues receiving an over-dose [4].

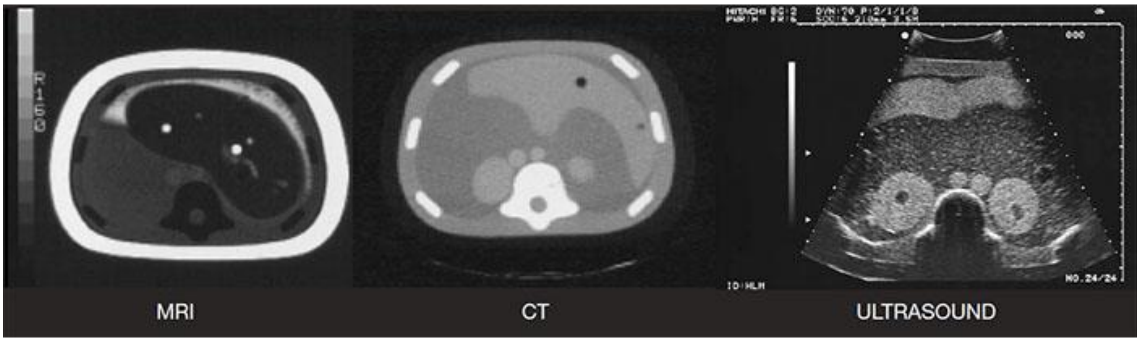

Figure 4.1 – MR, CT, and US images. *Courtesy of Supertechx-ray*[4.1]

Laparoscopic interventions shown in figure 4.2 are in some cases preferred over traditional surgery because of less wound pain, shorter hospitalization time, fewer postoperative wound complications, and less disfigurement [5]. The advances in medical technology enabled the proper application of these kinds of procedures in different medical specialties. The progress in Robotic-Assisted Surgeries (RAS) and Image-Guided Interventions (IGI) have especially reinforced the implementation of MIS worldwide.

[4.1] https://www.supertechx-ray.com/Ultrasound/TrainingPhantoms/CIRS-057A.php

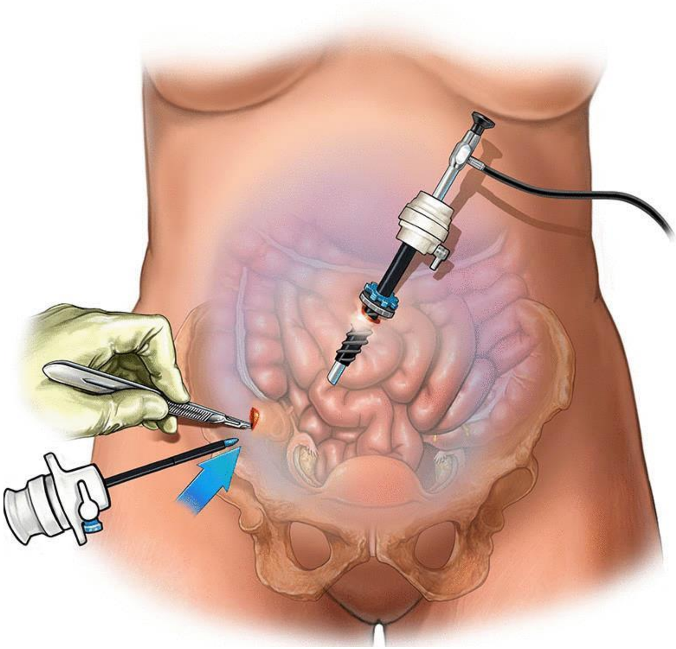

Figure 4.2 - Laparoscopy courtesy of Healthdirect

Despite its many advantages, MIS encounters multiple challenges that limit its adoption. Some of the limiting factors are the reduced maneuverability of tools, lack of haptic feedback, loss of stereopsis (perception of depth and three-dimensionality), and the extended learning curve [6]. These aspects are decelerating the widespread of MIS procedures in several disciplines. Additionally, it is worth mentioning that the innovation in the MIS field must take into consideration the ergonomics of the operative room through technologies that allow effective communication and optimal working space for the medical staff.

The implementation of MIS procedures broadens across a spectrum of medical specialties. These surgical fields include urology, gynecology, general surgery, neurology, oncology, gastroenterology, cardiology, and others. It is greatly important to overcome the challenges that MIS encounters in order to increase the safety and precision of surgical procedures.

Robotic surgical systems enable the automatization of several medical procedures while ensuring the safety of the medical staff and the patient [7]. Potential applications of robotic needle steering in the field of liver oncology include percutaneous procedures such as biopsy in figure 4.3, tumor ablation, and injections [8]. The stability and dexterity that these systems offer can improve the accuracy and precision of percutaneous procedures. Nonetheless, the implementation of these systems requires safety considerations that involve strategies to re-plan, abort, and decide whether to continue or stop the clinical procedure.

[4.2] https://www.healthdirect.gov.au/laparoscopy

Figure 4.3 - Percutaneous liver biopsy. *Courtesy of National Cancer Institute*[4.3]

4.2 Clinical State-of-the-Art in Robotics for Liver Oncology

Robotic surgical systems intend to facilitate the work of many medical specialties [9]. They have been widely implemented in pulmonology, ophthalmology, cardiology, and neurology as well as in urology and gynecology. These systems can overcome the limitations in conventional and MIS procedures.

So far, the most successful system is the da Vinci Robotic Surgical System (Intuitive Surgical, Mountain View, CA, USA). This system is formed by consoles developed for teleoperated surgery. The surgeon intuitively controls a slave unit, made of up to four robotic arms and a 3D HD camera [10]. Da Vinci has been characterized as a game-changing technology [11].

One of the main obstacles to the da Vinci platform is the cost. It is difficult for hospitals to buy this system since it costs 1.85€ million, with a yearly service charge of 150 000€ and an instrument cost of approximately 2300€ per case [6]. It is expected from the competitive market a decrease in the expenses and an increase in the availability of robotic surgical systems [11]. The system developed by Surgical Intuitive announced in 2021 that the robotic platform had surpassed 10 million procedures worldwide [12]. Figure 4.4 displays the latest version of the da Vinci systems, da Vinci Xi. This robotic system was released in 2014 [11].

[4.3] https://unsplash.com/@nci

Figure 4.4 DA VINCI XI SYSTEM (2014). The Surgeon Console on the left, the Vision System in the middle and the Patient-side Cart on the right. *Courtesy of ELvation Medical GmbH*[4.4]

Senhance surgical system (TransEnterix Surgical Inc, Morisville, NC, USA) received in 2000 FDA clearance to perform procedures in the general surgery and gynecologic fields [11]. This system provides an ergonomic seat placed in an open console, called the 'cockpit' and a monitor provides 3D HD visualization with the use of polarized glasses [11]. The camera manipulation is controlled by the surgeon's eye movements through an infrared eye-tracking system. The system centers the image at the point the surgeon is looking at. The handles are based on laparoscopic instruments and offer haptic feedback, which can help in a smooth transition for laparoscopic experienced surgeons [11].

Robotic-assistance in liver oncology procedures has been rarely used compared to other procedures such as gastro-intestinal and urological [13]. It has been argued that insufficiency of instruments and technical complications for liver oncology are probably appropriate justifications for the limited use of robot assistance in these procedures. This has motivated researchers to investigate the potential of different robot-assisted medical systems to treat tumors in the liver. This chapter introduces the current clinical state-of-the-art in robotic systems for liver oncology and the potential clinical applications in liver oncology.

Kato Y, et al [14] conducted a thorough study on 46 hepatocellular carcinoma (HCC) patients who were treated by robotic liver resection (RLR). The study tested whether RLR is feasible and safe enough to be used for HCC by comparing the anatomic resection to the non-anatomic resection procedures. The study concluded that anatomic and non-anatomic RLR can be safe and applicable to select HCC patients. However, further studies need to be done on a more diverse and larger number of patients to further assess the safety and applicability of RLR.

4.3 Potential Clinical Applications in Liver Oncology

For liver Oncology, different clinical operations could be used to detect, locate, and remove (treat) the cancerous cells. Liver biopsies such as percutaneous, laparoscopic, and transvenous are widely used to detect and locate tumors in the liver by taking a sample of the tissue. Biopsies can be technically challenging to be able to locate the tumor accurately with the least number of samples taken from the patient and the least amount of damage to the tissues and future complications. The same is true for ablations and hepatectomy which can be solutions to treat the tumors by overheating

[4.4] https://www.elvation.de/da-vinci-systeme/

and killing the cells or removing them respectively. In [15], it is argued that the safety and feasibility of robotic-assisted laparoscopic anatomic hepatectomy are guaranteed with fewer complications compared to conventional laparoscopy. However, the cost of such robotic systems can be very high, therefore more studies and development of these systems are crucial for commercial use. For relatively large irregular-shaped tumors, a much more complex operation should be performed with high accuracy. In [16], robotic-assisted microwave coagulation is used to kill the tumor cells. They used three robots to perform the operations. Therefore, an automatic planning algorithm is implemented to take into consideration the deformation of the tissues while operating and to produce maximum speed and accuracy. Although the algorithm considered the avoidance of other tissues and the ribs, motion compensation while breathing needed to be integrated. Musa M J. [17] developed a robot specialized in treating tumors by providing respiratory motion compensation. The results showed significant improvement in accuracy when the motion compensation algorithm was activated with slight errors due to fabrication deviations and registration errors. The robot has the potential to treat HCC patients in a safer and more efficient way. Robot-assisted minimally invasive interventions are being developed to potentially improve the efficiency of such operations. However, the applicability and the safety of such systems are being investigated to convince physicians to replace their conventional methods. Teleoperated robots need to mimic the haptic and visual feedback experienced by physicians during open surgery.

Additionally, the imaging modalities provided using technologies such as augmented reality (AR) can eliminate a lot of the problems that the surgeon might face. For instance, the differentiation of tissues in the liver or the exact location of the needle relative to the liver where a tumor needs to be accurately identified. Moreover, haptic feedback and automatic mechanical stops can provide the physician with enough information to localize the needle's position for safe operation to avoid intervening in critical tissues. These features will add a new dimension to minimally invasive interventions on the liver for safer and more efficient performance when dealing with complex operations. Potentially, this application allows novices to operate earlier and more often on patients since a substantial number of risks are avoided.

4.4 Discussion

The implementation of robotic surgical systems in MIS offers an interesting approach to addressing the current limitations and challenges that MIS holds. Some of these challenges are poor visibility, hand tremor, dynamic changes, and unstructured and easily deformable workspaces [18]. Robotic systems offer the possibility of improving precision, stability, and dexterity during MIS. However, there is still a tremendous need to improve current robotic systems since they are unable to navigate tortuous paths and might be affected by instrument clashing [18]. Safety is crucial in liver oncology procedures due to the critical tissues of the nearby gallbladder, veins, and arteries. Additionally, the economic viability of teleoperated systems needs to be evaluated for further implementation in the liver oncology field.

5 Technical aspects: Navigation

5.1 Introduction

Navigation is a collective term that describes any workflow where patient scans, real-time tracking, and, occasionally, computer-aided planning are combined into real-time spatial information that provides orientation and sometimes even guidance to reach the target location during an intervention [19]. The main benefit of this technology is the possibility to precisely indicate where structures of interest are located relative to the surgical tools in 3D. Preoperative imaging and planning, registration, and intraoperative navigation where tools can be tracked are essential components of the clinical navigation workflow.

Surgical navigation is achieved by combining the information provided by the tracking systems with imaging modalities such as MRI, CT, or US. There exist many medical procedures that rely heavily on precise tracking of the instruments. spinal surgery, endovascular aneurysm repair, and transcatheter tricuspid valve repair are examples of medical interventions which depend on the tracking of surgical tools.

5.2 State-of-the-Art in Clinical Navigation Technologies

5.2.1 Imaging systems

Computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound (US) are imaging modalities widely implemented in the treatment and diagnosis of several medical applications. The success of percutaneous image-guided procedures depends on the accuracy and precision of needle placement [3]. Imaging modalities hold an important role during percutaneous image-guided procedures. In percutaneous procedures occurring in the abdomen or the thorax, it is usually needed to have a good spatial and temporal resolution [20]. However, these systems fail in providing simultaneously good spatial and temporal resolutions. For instance, MRI provides high-quality images but has a low update rate acquisition. Whereas ultrasound provides low spatial resolution real-time images. The current limitations compromise the accuracy and precision required for percutaneous procedures, prolong the time of intervention and demand highly trained medical staff.

The use of intraoperative MRI and CT is limited by the large size of the equipment and the data acquisition time increases the duration of the surgical procedure. Advances have been made in these modalities to make them more suitable for the operative room. For instance, C-arm is a new imaging technology that produces 3D images more quickly, consumes less energy than CT, and produces a lower irradiation dose. Some examples of commercially available C-arm systems are Veradius Unity (Philips) shown in figure 4.5 , Vision RFD 3d (Ziehm), and CIOs Spin (Siemens). Additionally, a novel system can be attached to the wall or ceiling of the operative room to provide more flexibility to the positioning of the system and improve the ergonomics of the operative room.
Intraoperative MRI (iMRI) is used to evaluate the presence of any residual tumor after resection [21].

Figure 5.1 - Philips Veradius C-Arm. *Courtesy of Equipped MD*[5.1]

Nevertheless, this technology has certain limitations such as the need for an operative room with MRI-compatible devices, its high cost, and the need of interrupting the surgery during the acquisition time which increases the time in the operative room. A powerful alternative that is thought to overcome some of the challenges that iMRI encounters is intraoperative 3D US (i3DUS) [21]. Some of the advantages that i3DUS has are real-time data acquisition, no disruption of the working space in the operative room, and its low cost. However, i3DUS does not offer the high resolution that it can be obtained through MRI, and it is difficult to interpret US images. Shapey et al. [22] acknowledged these challenged concerning i3DUS and developed a system capable of integrating multi-modality image-guided data for navigation in neurosurgery. The system can integrate preoperative 3D CT or MRI with live reconstructed 3D ultrasound. The prototype needs further work to improve the system autonomy and robustness. Nevertheless, it explores a future direction that might overcome the limitations of i3DUS and lead to the integration of multimodal images in navigation.

5.2.2 Registration

Registration consists in aligning two or more frames throughout mathematical transformations [19]. Possible examples of these frames could be images, surgical tools, medical systems, patients, robotic systems, etc. Combining complementary information of different patient scans allows for a more complete model of the patient. For instance, the registration of MRI and PET would allow the combination of metabolic information and proper localization of such activity through the different anatomical structures. Registered patient scans are sometimes shown in composite views, where information from multiple scans is condensed into a single “fused” visualization.

Image registration is the process of overlaying images obtained from different imaging modalities. It can be a challenging task in terms of accuracy, effectiveness as well as robustness. Examples of image registration include mosaicking of images, shape recovery from stereo vision, motion tracking as well as tracking the growth of tumors. It is convenient to consider dimensionality since it specifies the dimensions of different possible registration approaches. The different combinations of dimensions include 2D-2D, 2D-3D, or 3D-3D, these are subject to the imaging acquisition system.

[5.1] https://www.equippedmd.com/product/philips-veradius-c-arm/

Different methods are used to implement the image registration process. Traditionally, image registration or image alignment algorithms can be classified into intensity-based and feature-based [23]. Intensity-based methods compare intensity patters in images via correlation metrics, while feature-based methods find correspondence between image features such as points, lines, and contours.

The registration workflow usually includes feature detection, feature mapping, transform model assessment, and image transformation [24].

5.2.3 Tracking

Tracking consists in determining the position of objects of interest, such as surgical tools, in the intraoperative coordinate system [19]. For this, a tracker can be attached to a surgical tool that needs to be navigated. It is crucial that the tracker is placed at a predefined position on the surgical tool, and that the tool is calibrated relative to the navigation platform. This calibration, in combination with the tracking information of the surgical tool tracker, allows tracking of the tip of the tool thereby providing navigation from the perspective of the tip of the surgical tool.

There exist two main types of tracking systems, optical and electromagnetic tracking systems. Optical tracking systems are characterized by high accuracy and robustness when dealing with the site of interest [25]. The working principle relies on tracking the position and orientation of surgical instruments by using the light of the optical spectrum. On the other hand, electromagnetic tracking systems provide fast and accurate tracking of surgical instruments by using an electromagnetic field.

These technologies have influenced greatly the navigation surgery field and for some surgeries, they are considered the gold standard. For instance, optical trackers are considered the gold standard for navigated surgery of the sinus, frontal skull base, and lateral skull base [25]. Additionally, they have been widely employed as navigation systems in the fields of cardiology, otorhinolaryngology, and dental [25]. Electromagnetic tracking systems have been proven to provide spatial accuracy for thermal ablation and for total knee arthroplasty [26,27].

An example of commercially available electromagnetic tracking is the Aurora ED electromagnetic tracking system (Northern Digital, Waterloo, Canada) shown in figure 4.5 [25]. This system enables the localization and visualization of surgical tools by linking the position and orientation of the EM tracker in the 3D patient space [28].

Figure 5.2 - Aurora NDI. *Courtesy of Northern Digital Inc*[5.2]

5.3 State-of-the-Art in Motion Compensation

5.3.1 Respiratory Motion

The intentional or unintentional movements of the patient are known as intrafraction motion. This motion is a limiting factor that affects the accuracy of many diagnostic and therapeutic image-guided procedures. Intrafraction motion is induced by a combination of different systems, such as the respiratory, cardiac, and gastrointestinal systems [13]. Moreover, percutaneous procedures include medical procedures where access to the site of interest is performed through the insertion of a needle at the level of the skin towards inner organs or soft tissues.

Intrafraction motion, especially respiratory motion, limits the accuracy of percutaneous procedures since the target position changes with time, and systems fail in providing real-time visualization and high spatial resolution [20] Respiration is considered the main cause of inaccurate targeting, especially in liver biopsy and tumor ablation [29]. The literature offers different strategies to correct the inaccuracies produced by respiratory motion [13,8].

Breath-holding: A simple approach that is currently applied in the clinic. This method requires pre-operative and intraoperative imaging data of the site of interest to be acquired during a patient's breath-hold. The intervention time is limited by the number of times patients can hold their breath, usually 30 seconds. Additionally, this approach might be inadequate for some patients.

Respiratory gating: This method involves working during a limited window based on a concrete phase of the respiratory cycle (such as the end of inhalation or the end of exhalation). The restrictions in time significantly prolong the intervention time.

Forced shallow-breathing: This percutaneous approach places a plate against the abdominal region of the patient and employs a stereotactic body frame to perform the insertion.

Motion-encompassing methods: In this method, the entire range of motion and the mean position of the tumor are estimated by using imaging modalities.

Motion tracking: This method is an attractive approach for which points of interest are tracked. The potential real-time resolution that this approach offers makes it a suitable option for addressing motion correction. There exist four motion tracking methods:

- Lesion imaging.
- Imaging the site of interest with implanted fiducial markers.
- Locating signals from active or passive devices placed in or near the lesion.
- Estimating the location/motion of the lesion using a surrogate signal that is highly correlated with the tumor's motion.

Estimating the tumor's location and motion through motion tracking techniques is a convenient approach that could improve the current conditions of image-guided percutaneous procedures and reduce the current acquisition/intervention time. The motion induced by respiration can be estimated by using the information of a surrogate signal, and imaging data of the site of interest [3]. McClelland *et al.* reviewed the common components that motion model studies comprise [8].

- Surrogate data: These signals measure indirectly the lesion's motion. Surrogate signals are required to have a strong relationship with the induced motion, a fast-updating time, and should be easy to measure.
- Motion representation: Motion measurements of the actual region of interest involve using imaging data. Alternatively, these measurements can be obtained using other types of sensors such as electromagnetic and optical tracking systems.
- Correspondence model: These models establish the relationship between respiratory induced motion and the surrogate signals. The instantaneous position of the lesion can be obtained through these models.
- Fitting method: Method applied to fit the correspondence model to the training
- set, typically through supervised machine learning algorithms.

5.3.2 Surrogate signals

The literature offers different solutions based on the implementation of surrogate signals to solve the problem of respiratory-induced motion. There exist two types of surrogate signals, one-dimensional scalar data, and complex data [8]. Typical examples of scalar surrogates are MR navigator echo, respiratory bellows, and spirometers. Additionally, optical trackers, electromagnetic, or laser-based tracking systems can be implemented. On the other hand, there are two types of higher-dimensional data: surfaces, and images. For instance, time of flight cameras can acquire 3-D skin surfaces [8]. On the other hand, imaging systems can be used to obtain the target position. Typical imaging modalities used to record the actual motion of the tumor are:

- Magnetic Resonance Imaging
- Computed Tomography
- X-ray
- PET/SPECT
- Ultrasound

It is worth mentioning that some studies have proposed measuring the motion of the lesion by means of electromagnetic tracking rather than imaging [29,8].

A common surrogate signal implemented for RME using MRI is MR navigator echo signals. These signals can measure the position of a lesion by exciting a small column of magnetization [8]. King *et al.* created a subject-specific respiratory motion model capable of combining MRI and PET imaging and estimating the real-time motion through navigators [30]. Moreover, respiratory bellows are placed between the subject's abdomen and a firm surface. The surrogate signal is obtained by measuring the air expelled from the bellows. Spirometers are used to measure the airflow to and from the lungs, they have a high correlation with respiratory-induced motion. However, one problem with using spirometers and respiratory bellows is that there can be drifts in the signal due to errors related to the instrumentation and/or air leakage [8]. Optical markers, electromagnetic and laser-based tracking systems have been proposed to overcome this problem.

Fahmi *et al*. developed and validated a respiratory motion estimation approach that estimates the Superior-Inferior motion of a lesion in the liver using external markers as surrogates and MRI-acquired liver motion [20]. Multivariate linear regression, and Ridge and Lasso regressions were utilized as supervised learning fitting methods. It was observed that Lasso generally outperformed multivariate linear regression and Ridge. They demonstrated that more than one external marker is needed to obtain high accuracy. Additionally, the estimation accuracy was higher when the marker was located close to the umbilicus.

Abayazid *et al*. proposed a method based on the insertion of a reference needle into a moving organ to estimate the real-time target motion [29]. The needle's position was measured using an inertial measurement unit (IMU). In this study, an electromagnetic sensor was used to locate the target's position. The correspondence model was validated while changing the conditions of the experimental protocol to test the effect of different factors. The evaluated parameters were the insertion angle, target depth, target velocity, and proximity to the needle.

Moreover, Berijanian *et al*. compared the performance of two different surrogate signals, optical markers, and IMU [31]. This study included the development of a robotic phantom to simulate the respiratory motion of the liver, diaphragm, and abdomen skin in two directions, superior-inferior and anterior-posterior. The liver had incorporated a spherical tumor, and the displacement of the tumor was measured by means of an electromagnetic sensor. It was observed that no surrogate signal outperformed the other but using the two surrogate signals in conjunction reduced the estimation error. Additionally, this study investigated the effects of different parameters (liver elasticity, tumor size, and tumor location) on the tumor's motion.

Reference	Motion Model	Surrogate Signal	Validation Experiments
Vashistha et al. (2021) [32]	CT	Optical Markers	Motion Phantom
Remy (2021) [32]	MRI	Internal and external markers	Human Subjects
Lappas et al. (2020) [4]	MRI	Ultrasound	Human Subjects
Abayazid et al. (2018) [29]	EM	IMU	Motion Phantom
Berijanian et al. (2018) [31]	EM	Optical Markers and IMU	Motion Phantom
Fahmi et al. (2017) [20]	MRI	Optical Markers	Human Subjects
Baumgartner et al. (2017) [15]	MR	MRI	Human Subjects
King (2011) et al. [34]	MR	MR	Human Subjects
Schweikard (2000) et al. [35]	X-ray	IR	Human Subjects

Table 2. Summary of respiratory motion estimation studies

5.3.3 Devices

Current devices explored in [36]:
Synchrony: Respiratory tracking system that continuously synchronizes radiation beam to the motion of the tumor. The external respiratory motion is tracked using three optical fiducial markers attached to a tightly-fitting vest. Small gold markers are implanted near the target area before treatment to ensure the continuous correspondence between internal and external motion.

Calypso: prostate motion-tracking system integrated into Varian, eliminated the need for internal-external motion modeling by implanting three tiny transponders with an associated wireless tracking.

BrainLAB ExacTrac: positioning system uses radiopaque fiducial markers, implanted neat the target isocenter, with external infrared (IR) reflecting markers. Internal markers are tracked by an X-ray localization system, while an IR stereo camera tracks the external markers.

Xsight: Lung Tracking system (extension of the CyberKnife system) is a respiratory motion-tracking system of lung lesion that eliminates the need for implanted fiducial markers.

5.3.4 Patient perspective

Patients receiving ablation will be treated under full anesthesia. During the placement of the needles the ventilation can be paused to place the needles. However, during biopsies, patients will receive local anesthesia and will need to perform breath holds during needle placement. These breath holds are particularly challenging in patients with a compromised respiratory function. These patients show lower mean maximum breath holds compared to patients with healthy respiratory function (25 versus 45 seconds) [37]. Moreover, these patients were able to perform less repetitions of 12-second breath holds (4.9 versus 6.6) [37]. Although even patients without compromised respiratory function could have difficulty holding their breath and following the exact breathing instructions [38,39]. Moreover, multiple prolonged breath holds could lead to discomfort of patients undergoing these interventions. By implementing robotic assisted needle placement, the comfort of the patient could be optimized.

5.3.5 Clinical perspective

Today, thermal ablation (TA) is increasingly used as the golden standard treatment for various unresectable tumors [40, 41]. Several studies have shown that TA is a less invasive treatment option leading to a shorter in-hospital stay and lower costs compared to surgery [42-44]. However, in terms of local tumor recurrence (LTR), TA is associated with high rates ranging from 4.3 to 48% [42, 45-51]. A contributing factor for these high LTR rates is insufficient ablation margins partly due to inaccurate placement of the ablation needle. In literature, the recommended minimal ablation margin is at least 5 mm and a margin of >10 mm is preferred [52]. In the clinic, the minimal ablation margin is most commonly assessed by comparing cross-sectional images (i.e. Contrast-Enhanced Computed Tomography (CECT) and/or Magnetic Resonance Imaging (MRI) scans) in side-by-side juxtaposition. However, these assessments proved to be challenging as a high number of misjudged tumor margins are observed [53]. By improving the accuracy of needle placement sufficient minimal ablation margins could be achieved, which may result in a reduced LTR rate after ablation.

5.4 Business Aspects

According to market research, the global surgical navigation system market size was about 730 million USD in 2017. With an expected compound annual growth rate (CAGR) of 7.0%, the forecasted value of the total market size for 2025 is 1.25 billion USD [54], [55]. The current navigation market comprises mainly application areas, such as neuro, orthopedic, spine, trauma, ENT, dental and cardiac. North America takes a share of 36% of the total market, driven by the developed healthcare system and increasing demand for shorter hospital stays and better patient outcomes and thus, the adoption of minimally invasive surgery.

5.4.1 Trends

Traditionally the used tracking technologies are mainly optical and electromagnetic systems. A larger growth of the optical solution is still expected, due to its versatility and proven accuracy. There is a trend to use more and more hybrid solutions to track instruments and devices, including non-rigid devices, inside the body, without a line of sight.

The integration of tracking in the imaging equipment to streamline the workflow and enable real-time navigation on intra-operative imaging is certainly a trend caused by the collaboration amongst the players in the industry. Also, instrument and device companies are more and more involved to interface with navigation systems.

The latest key trend is the use and development of augmented reality, where live view of reality (e.g. patient), direct or indirect, is enhanced with virtual- and medical image-information. This presents a more intuitive and understandable image to the physician.

A relevant example of image based tracking during surgical navigation can be found in the Philips ClarifEye system which integrates 4 optical cameras in the X-ray detection system. It combines imaging and augmented reality (AR) navigation in one system to support precise planning and effective device guidance for accurate screw placement during spinal surgery procedures.

Figure 5.3 – Philips ClarifEye system, which integrates optical tracking of surgical devices during spinal surgery procedures.

5.4.2 Growth Drivers

Various factors can be identified in the growth of the surgical navigation market. One is the aging population, which results in more orthopedic, spinal and neurological treatments. This is amplified by the demand to do these treatments minimally invasive, with the benefit for the patient of smaller incision wound, less chance of infection and quicker recovery with the economic benefit of shorter hospital stay and outpatient treatment. The economic benefit also creates good base to reimburse MIS with the use of surgical navigation systems.

The demand for more outpatient treatment has increased the number of ambulatory surgery centers (ASCs) and office-based labs (OBLs). ASCs can carry out the same complex procedures as in a hospital in a fully sterile environment. Sometimes they are even part of or located at the hospital campus.

ASCs and OBLs do not offer overnight stay, the operations are done faster, easier, in a more efficient and predictable way, which creates a new market for surgical navigation systems.

5.5 Discussion

The future of navigation aims in reducing the size of the imaging equipment and integrating multimodal image-guided data. The market share of medical robotics is increasing and is expected to increase with a higher rate when the high-tech equipment become cheaper, and surgeons have more trust and experience with such technology. Using tracking systems inside MR rooms will be much more feasible when non-ferromagnetic optical trackers becomes cheaper and more efficient. This will lead to less usage of the electro-magnetic trackers, since they cannot maintain their accuracy inside MR rooms.

To avoid inconvenient breath holds especially for an aging demographic in Europe, a lot of researchers are now working on estimating the motion of the patients' organs during breathing inside MR rooms. This is a great motivation for researchers to develop tracking systems to be more efficient and resilient inside MR rooms. Consequently, robot-assisted interventions will be upgraded such that semi-autonomous robots will be used to track tumor location when performing ablations or biopsies.

6 Surgical cockpit: types of feedback

6.1 Introduction

Medical robotics is getting more popular in the research field as the need for integrated assistance during surgeries increased over the past decades. Surgeons have been processing large amounts of data that have grown exponentially over the last decades due to the digitalization of clinical practice, leading to cognitive overload [56]. Since then, surgeons have been dealing with more problems while comprehending and analyzing vast amounts of data through electronic medical and health records, which developed more errors and increased the chance of patients' dissatisfaction. Researchers were motivated to develop objective techniques to monitor surgeons' cognitive load nearly in real-time during work and compare that with error occurrences [57], which helps in a deeper understanding of the surgeons' struggles. Hence, sophisticated cognitive support systems can be developed to fulfill their needs. In [58], a similar study was done to monitor cognitive load data during different surgery times of a cardiac surgery team. The preventable error was recorded to finally conclude that a distraction of one of the team members caused that error. Root cause analysis was employed to thoroughly investigate any physiological indicator of cognitive overload rather than concluding that errors happened for lack of experience or ineffective supervision. The results of the root cause analysis suggest that frustration and anger erupting in the surgery room and the lack of consistent guidance by the experienced mentor caused a temporary cognitive overload to the amateur surgeon. Coping mechanisms may then be implemented to support the anesthesiologist when dealing with cognitive overload by monitoring the heart rate or HRV measures, etc.

In [59], an in-depth study was done to investigate the effects of information technology in our lives in general and in the workplace and how they affect the cognitive load, which ultimately impacts the decisions made in the workplace. These studies provided objective empirical data based on physiological indicators of the medical staff's biological systems that motivate the medical roboticists to optimize the data delivered to the medical workers. Surgeons mainly depend on images as primary data to act. However, the tremendous amount of data could be overwhelming and not that beneficial. Therefore, augmented reality should be incorporated into the existing systems to analyze the images and deliver them to the surgeon rather than just producing raw data that needs extra comprehension from the physician's perspective.

Furthermore, haptic feedback can be a huge step forward in the surgical arena. It can provide safer and more precise operations on the patient without the need to analyze complex information. It can also increase the autonomy of the operation to lift a substantial amount of work from the physician's burden. In [60], it has been argued that haptic feedback can enhance surgeons' performance and counter the effect of cognitive load, which is already a problem for most surgeons. Novice surgeons using haptic feedback in the ProMIS simulator shown in figure 6.1 increased speed and accuracy by 36% and 97%, respectively, compared to the MIST-VR simulator, which has no haptic features. The study predicts that these results can be even better when the experiments are applied to experienced surgeons.

Figure 6.1 - ProMIS simulator. *Courtesy of Wiley Online Library*[6.1]

This section looks into the history of image-guided surgery and the state-of-the-art equipment and techniques of minimally invasive image-guided interventions. Furthermore, applications that use haptic feedback are investigated to further advance the present medical equipment that does not possess haptic features and to examine whether they can be compatible with such features. Finally, work related to the interaction between the imaging and haptic data through augmented reality (AR) is reviewed to provide more meaningful information to the surgeon. It is crucial to skip a large amount of non-optimal data that burn out the team during an operation and lead to stress and wrong decisions. Also, current teleoperation systems are reviewed whether they are in the medical field or other fields.

6.2 Visual

Image-guided surgery has been massively developing for approximately the past 40 years. However, surgeons have been using images in medical operations since 1895, when the first therapeutic surgery used x-ray images [61]. Since then, a series of image-guided interventions based on X-ray images and radiography have been performed to remove foreign objects from the patient's body. Then, Horsley& Clarke [62] developed a device named the stereotactic frame shown in figure 6.2. It used the monkey's head as a fixed frame to assign the Cartesian coordinate system and aligned it using external markers. This device established the foundation for 100 years of image-guided

[6.1] https://onlinelibrary.wiley.com/doi/full/10.1111/vsu.12483 interventions [63]. Image-guided interventions were practically mostly only applied in neurosurgery in the 20th century, as the skull is the only body part that provided a stable fixed frame. After introducing computer tomography (CT) scans in the 1970s and the personal computer in 1981, the stereotactic frame device was used more often in mainstream neurosurgical practice. From 1987 to 1989, Peters, et al. [64][65] developed an effective and inexpensive PC-based system to plan stereotactic procedures with CT, magnetic resonance imaging (MRI), and digital subtraction angiography [66]. It paved the way for many stereotactic surgeries such as biopsy and aspiration of lesions, implantation of electrodes to record deep EEG signals, and radio-surgical techniques.

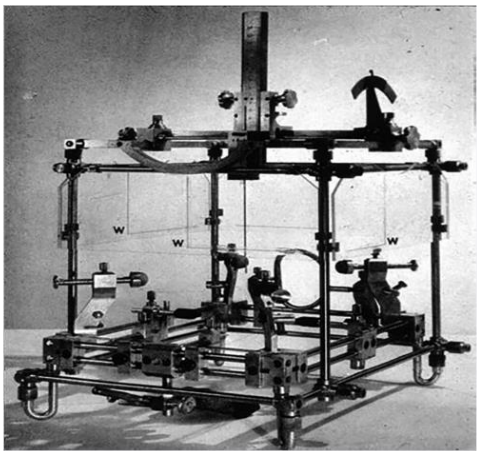

Figure 6.2- Stereotactic frame designed by Horsley and Clark used for neurosurgical practices. *Courtesy of Neupsy Key*[6.2]

Afterward, a system was developed by David Robert's lab, which introduced a frameless stereotactic operating microscope that accurately located the target and produced a dynamic tomographic image. The image illustrated the correct scale, position, and orientation using fiducial points on the patient's external anatomy [67]. A prototype was built to realize the idea of the frameless stereotactic microscope which provided great potential for precise stereotactic guidance with more broad applicability and less stereotactic equipment that may be an obstacle for the physician [68]. In [68] and [69], the concept was extended to produce three orthogonal CT images on a dynamical display to localize the surgical positions of a developed articulated arm that frees the neurosurgeon of the mechanical and computational maneuvers that needed to be considered with an accuracy of less than 1 mm. It has provided a more intuitive way to accurately realize 3D surgical navigation after a significant improvement in the imaging and computation capabilities by the end of the 1980s.

Tracking: To unlock the full potential of image-guided interventions, one would need a reliable tracking system to localize the surgical instruments used in real-time. The state-of-the-art tracking systems that are commonly used in surgeries are; optical video-metric, optical active and passive infrared, and electromagnetic. Optimal video-metric tracking systems depend on calibrated video cameras that identify and track marker patterns to localize the target. One of the commercially available small-sized systems that are used in the medical field is the MicronTracker developed by Claron Technology Inc. Another type of tracking system is the optical infrared such as Polaris, which Northern Digital Inc develops. It is a wireless system that combines both passive and

[6.2] https://neupsykey.com/2-a-brief-history-of-brain-stereotactic-frames/

active optical systems tracked by CCD cameras. Although these optical systems have higher accuracy than their electromagnetic counterparts [70], the electromagnetic ones such as Aurora from Northern Digital Inc shown in figure 6.3. and the microBIRD from Ascension Technology Corp are also widely used. The electromagnetic systems have minute sensor coils that can be easily fitted in surgical instruments inside the body and are not affected by light deficiency as optical systems are. Furthermore, such systems are created now to be more robust and resistant to metal over-sensitivity and can be customized to the operating room environment.

Figure 6.3 - Polaris Vicra NDI. Courtesy of Northern Digital Inc[6.3]

Endoscopic Camera: The first known endoscope was invented by Dr. Philip Bozzini in 1804 (90 years before the first image-guided surgery) and called "Lichtleiter" or "light conductor" [71]. He wanted to allow the physician more visual access to the patient's inner cavities. He used a candle situated in a funnel-shaped sheet of metal, as shown in figure 6.4, a mirror to project the light to the other end of the metal sheet, and an eyepiece to allow the physician to look into the larynx of the patient. The endoscopes continued developing until Maximilian Nitze developed the Cystoscope in 1877, which widened the field of view to visualize the urinary bladder through the urethra. The same concept of the Cystoscope was used by Hirschmann in 1901 and Dandy in 1922 to view the maxillary sinus and perform a choroid plexectomy, respectively [72].

Figure 6.4 – "Lichtleiter" or "Light conductor developed by Philip Bozzini in 1804" Courtesy of Isaac Hayes[73]

In 1960, Harold Hopkins invented a new rod-lens system called the fiberscope, which used a bundle of fibers to transmit images rather than multiple lenses that originally produced terrible quality images. The same idea was used before by John Logie Baird (the inventor of the television). However, Harold developed the concept by realizing the effect of the number of fibers used on the resolution of the fiberscope [74]. Harold's

[6.3] https://www.ndigital.com/optical-measurement-technology/polaris-vicra/

solution image tereoHD video used in the Intuitive Surgical da Vinci Surgical System enables the medical staff in the surgical room to visualize the operative field with the highest imaging quality.

6.3 Mixed Reality

Nowadays, augmented, and virtual reality are becoming common in commercial and industrial applications. Augmented reality can be seen as the overlay between digital images generated and actual images as shown in figure 6.5 to provide more constructive information about the actual image that is not visually accessible. Virtual reality is the complete immersion in digital images without using real images. The ratio of the used virtual imaging to real images can differ according to the application and the outcomes desired. Therefore, a new term called "mixed reality" has been adapted to describe the multitude of possibilities between pure virtual reality and augmented reality, with the most significant emphasis on real imaging [75]. In the medical field, the optical view from a camera produces real images of the patient's body, medical instruments, and sometimes parts of the surgeon's body.

Figure 6.5 Augmented reality implementation during surgical interventions. Courtesy of Hospimedica[6.5]

The challenge of using AR in image-guided interventions is the importance of accurate alignment of the virtual image with the real image while the view is changing [79]. On the other hand, CT images, ultrasound, or MRI can be used to produce a virtual image consisting of certain information about the patient's anatomy. An overlay between these virtual and real images can facilitate the surgeon's comprehension for quick and accurate decision-making. In [67], mixed reality was first introduced to medical application in the 1980s when virtual preoperative images from CT were integrated with a microscope producing real images. The study used an acoustic referencing system and fiducial markers to unify the coordinate frames of the CT imaging data and the microscopic optical axis. Even though the paper was published about 40 years ago, it produced tremendous results with errors within millimeters. Since then, many scientists have developed different techniques to apply AR to other medical virtual imaging

[6.5] https://www.hospimedica.com/health-it/articles/294773132/augmented-reality-app-increases-biopsy-accuracy.html

[6.3] https://www.ndigital.com/optical-measurement-technology/polaris-vicra/

technologies. In [76], a system was developed to integrate obstetric ultrasonography with video camera images to show the 2D images projected within a pregnant woman using a head-mounted monitor, as shown in figure 6.6. This study did not rely on the conventional way of projecting 2D sonar images on an external monitor. However, it takes a significant step toward 3D scanning of ultrasound images to see through the external anatomy of the human body and acquire 3D ultrasonic data.

Figure 6.6 - Ultrasound image projected within a pregnant woman. Courtesy of Michael Bajura, et.al. (1992) [76]

In order to reduce microscope calibration errors for improved overlay of CT or MRI on the microscopic image, a calibration method was developed in [77]. It used a high-accuracy tracking system to allow free movement of the microscope without losing alignment with the virtual images previously constructed to ultimately obtain information about tumor volume, nerves, blood vessels, and bones. Although the concept of AR in medical applications has been used for some time, it was only recently used in interventional radiology and not merely for diagnosis [78]. In [79], an economical and efficient needle in spine insertion was successful using MRI data overlaid on the patient's body without using a head-mounted display device which is more convenient for the surgeon. Although that AR system does not provide real-time imaging, it shows critical regions close to the trajectory of the needle projected on the patient, making it applicable to spine insertions and musculoskeletal interventions that experience relatively little movements. The results showed a gradual decrease in root mean squared (RMS) errors when the system was used multiple times, showing excellent learning potential. In [80], a time-saving CT navigation system based on AR was used in percutaneous lung biopsy (PLB) to characterize small-sized pulmonary nodules. The system was tested on many patients, resulting in accurate diagnosis and few post-operative complications. Needle biopsy of the lung usually uses CT data to guide the surgeon through the patient's body to reach the target successfully and with the most significant level of safety [81]. Even though the addition of augmented reality provided a beneficial feature for image-guided interventions and a great potential for improved accuracy and safety, the increase in robot-assisted surgeries would need further development and integration of haptic feedback in teleoperations.

6.4 Haptics

The integration of haptic feedback features into the medical field will facilitate the surgeon's job to do the task with more efficiency and less cognitive load. Moreover, it will open the door to replace animals for simulators in surgical training sessions [82]. One of the earliest laparoscopic surgery simulators was designed in [83] to train inexperienced surgeons to perform a full cholecystectomy operation providing haptic feedback to feel the interactivity between the surgical instruments and the body organs being operated on. In [84], a robotic system with haptic feedback was designed to allow for teleoperation of CT-guided interventions to distance the surgeon from harmful X-ray radiations. The robot-assisted system was developed to help the percutaneous interventionist in needle insertion procedures such as biopsies and ablations with higher accuracy and critical tissues avoidance. The system design was developed to track forces acting on the needle up to 20 N with a high resolution and accuracy of less than 2 mm. These were excellent specifications to accurately palpate the different tissues as the needle depth changes into the organs. In [85], a more empirical study was conducted to test the automated laparoscopic grasper with force and visual feedback using a haptic feedback device called PHANToM shown in figure 6.7 (SensAble Technologies, Woburn, Massachusetts, United States) and a CCD camera. The study's objective was to determine whether visual feedback, force feedback, or both provide accurate results for tissue hardness characterization. After extensive tests on several subjects, the researchers concluded that force feedback produces higher accuracy than visual feedback to identify the hardness of the tissue and that combining both feedback systems produce the best results. In [86], the addition of haptic feedback features in minimally invasive surgical interventions raises many concerns on whether its theoretical benefits are realizable in practice.

Figure 6.7 - Phantom Omni developed by Sensable Technologies Courtesy of Delft Haptics Lab[6.7]

The study investigated the two opinions regarding the benefits of using haptic feedback in minimally invasive surgeries. Some studies consider force feedback to be of limited effect on the performance of the surgeon during laparoscopy [87][88]. These studies showed that force transmissions through the tissues are very hard to be robustly estimated due to the presence of too many contributing factors that affect the force reading such as the speed and depth of insertion. This may lead to misleading information observed by the surgeon and the main objective of adding such a feature in the first place will be lost. Moreover, limitations of haptic feedback sensations are considered, and whether there are significant benefits when experienced surgeons use the potentially expensive haptic feature.

On the other hand, most studies presented in [86] suggested that haptic feedback can improve the surgeon's execution and enhance the trainee's learning curve using simulators toward high fidelity performance. In [89], a haptic needle unit was explicitly

6.7 https://delfthapticslab.nl/device/phantom-omni/

developed for MR-guided biopsy. The design had some mechanical and control challenges that needed to be considered. MRI-compatibility challenges were overcome using antiferromagnetic ultrasonic actuators, piezoelectric ceramic actuators (PiezoLEGS), MRI compatible position sensors, and force sensors. The source-replica system consisted of a position and force control to steer the needle accurately and consistently produce correct force feedback sensations to the surgeon when different loading conditions are applied. A neural network based on the backpropagation technique was used to estimate the non-linearity of the motor's model for the source to compute the required frequency of the motors to achieve the desired motor's speed when a particular load is applied. In order to test the developed system, a physician was asked to distinguish between two different models, one containing a tumor and the other that does not. The physician successfully distinguished between the two models in all trials with a realistic sensation, but it was recommended for the design to be more ergonomic.

In [90], a teleoperation source-replica system shown in figure 6.8 was also used for MRI percutaneous interventional procedures focusing on prostate biopsy as the target procedure. A pneumatically actuated haptic robot is used as the source to sense the exerted forces on the needle from the tissues. The system also decouples the translational and rotary motions and provides two independent haptic feedback signals to sense the two different motions of the needle separately. A piezoelectric motor is used for the replica to position the needle in the desired location and orientation. A fiber-optic force sensor (FPI) is mounted on the motor to monitor the forces exerted on the needle. The system was tested for MRI compatibility, and the results showed that the user was able to position the needle with high accuracy (error<4mm). The haptic source sensor was also able to track the force feedback of the replica with RMS errors of about 2.5 N.

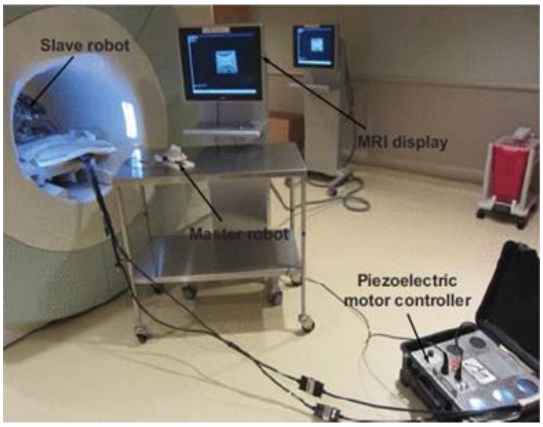

Figure 6.8 - Source-replica teleoperated MRI guided system based on Piezoelectric motors for needle insertion [90]

Transmission hydraulic pressure sensors and modified hydrostatic rotary actuators(MRI compatible) were used [91] to monitor a minimum of 0.1 N force changes exerted on a phantom membrane inside the MRI. The device developed targets trans perineal prostate interventions that exert a maximum force of 18N, which is 2 N less than the device's capabilities. The system relies on hydrostatic pressure measurements to calculate the forces exerted on the membrane rather than using actual force sensors on the end-effector. The results were promising as the system could position the needle accurately by feeding back the correct force values to the source(haptic hydrostatic rotary actuator).

6.5 Business Aspects

Augmented reality was valued at US$4.21 billion in 2017 and is expected to be worth $60.55 billion by 2023, growing at a compound annual growth rate (CAGR) of 40% during the forecast period, according to data published by MarketsandMarkets [92]. The head-mounted displays will hold a major share of the AR market. These devices have the greatest potential to drive the growth of the AR market. With advances in computing, AR-enabled devices would be used for applications in consumer, commercial and enterprise.

The global AR & VR in the healthcare market was valued at USD 2.01 billion in 2020 and is expected to grow at a CAGR of 27.1% during the forecast period. Advancement in technology and digitalization in healthcare, supportive government initiatives, increasing healthcare spending, surging usage in medical procedures, and training are critical factors that drive the adoption of the technologies for augmented/virtual reality in the healthcare market [97]. The growing demand for robotic processes rather than by-pass surgeries, upsurge in spinal disorders and brain-related difficulties, and growing need for cardiovascular surgery are some of the primary factors responsible for industry expansion for augmented & virtual reality in healthcare.

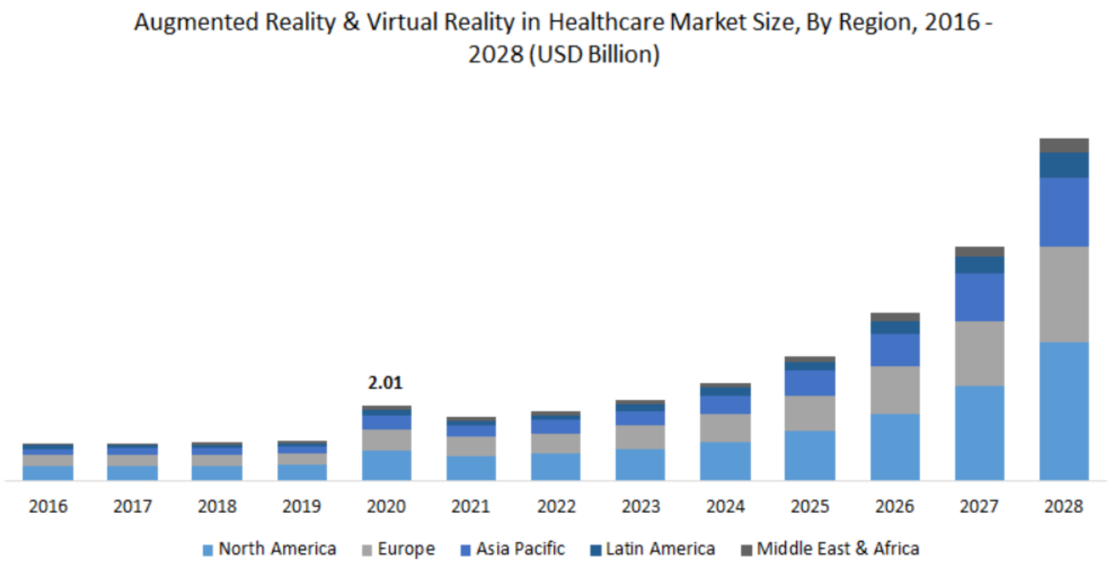

Figure 6.9 - Growth of the global AR/VR market in the healthcare sector [92]

The global market growth for augmented/virtual reality in healthcare will be mainly driven by the increasing number of surgeries across the world. The application of augmentation and virtual reality systems in surgeries, patient care management, and medical training and education is expected to boost the market's growth. The advancement in technology has resulted in the introduction of new products into the market, which will further increase the adoption of technology in healthcare. [97]

The major drivers for the growth of AR in the healthcare market are [93]:

- The increasing penetration of connected devices in the healthcare sector

- The increased investment in AR and VR healthcare by the major technology companies
- The growing need to reduce the healthcare cost

Given that AR is an emerging technology, there are still limitations and challenges, such as:

- The limited user interface affects the navigation performance and interaction experience of AR applications.
- Limited processing power, battery life, and storage, which are the major limitations of the AR market.
- Overcoming the challenge of changing the current way of working to increase the adoption rate.

The widespread use of AR in the healthcare industry will provide many new technical and clinical opportunities. The possibility for physicians to efficiently access information during an intervention will help them to conduct minimally invasive procedures that provides better outcomes for patients and increase staff satisfaction.
Healthcare organizations are predicted to spend as much as $5 billion globally on AR and VR by 2025 [94]. The key use of AR driving the growth of the AR market are: diagnosis and treatment of patients, improving ergonomics, teaching complex subjects to medical students, training doctors, managing logistics (e.g. device and medication inventory) and caring and supporting patients after they leave hospitals.

Haptic devices have been on the rise for the past 20 years after Force Dimension, the Swiss company entered the market with its Delta-3 haptic device. Since then, haptic devices have been widely used over Europe and north America especially in the medical field. Many developers also integrated other haptic devices with Omega-x to complement the user experience which makes these devices very agile and flexible in research.

6.5.1 Key players

Some of the most relevant players in the global AR healthcare market are: Google LLC. (U.S.), Microsoft Corporation (U.S.), DAQRI (U.S.), Mindmaze (Switzerland), Wikitude GmbH (Austria), Medical Realities (U.K), Atheer (U.S.), Augmedix (U.S.), Oculus VR (U.S.), CAE Healthcare (U.S.), Philips Healthcare (Netherlands & U.S.), 3D Systems (U.S.), Blippar (U.K), VirtaMed (Switzerland), HTC (Taiwan), Siemens Healthineers (Germany), Magic Leap, Inc. (U.S.), and Osterhout Design Group (U.S.) and Virtually Better (U.S.), among others [92].
Philips Healthcare announced its partnership with Microsoft in February 2019, where Microsoft HoloLens will be integrated into the Philips Azurion platform to aid efficiency in minimally image guided therapies [95].

One of the most important players in the haptic devices market that could be used for medical applications is Force Dimension with its state of art omega-x devices shown in figure 6.10.

Figure 6.10 -Omega 3, 5, and 7 respectively from left to right. *Courtesy of Force Dimension*[6.10]

6.5.2 Regional Analysis

North America is one of the leading regions in terms of market share due to the increasing adoption of consumer electronic devices, which is propelling the market growth to a large extent. AR in the healthcare market in Europe is expected to witness rapid growth in the forthcoming period whereas, Asia Pacific countries such as China, Japan, and India are emerging market, and are expected to grow at the highest CAGR in the coming years [92].

With respect to laparoscopic procedures in general, the projected surgical robotics device market is shown in figure 6.11. The global laparoscopic surgical robotic device market will experience strong growth over the forecast period. This growth will be driven by increasing acceptance and adoption of surgical robotic technology, regulatory approval for use in new indications that expand the addressable population, and an increase in clinical evidence that supports the benefits of robotic surgery.

The market will be driven by the entry of several new competitors and surgical robotic systems. Notably, the growing availability of smaller, more innovative, and lower-cost surgical robotic systems will allow these systems to become increasingly accessible for a greater number of facilities, resulting in increased adoption of surgical robotic systems in health care facilities in all countries covered. [96]

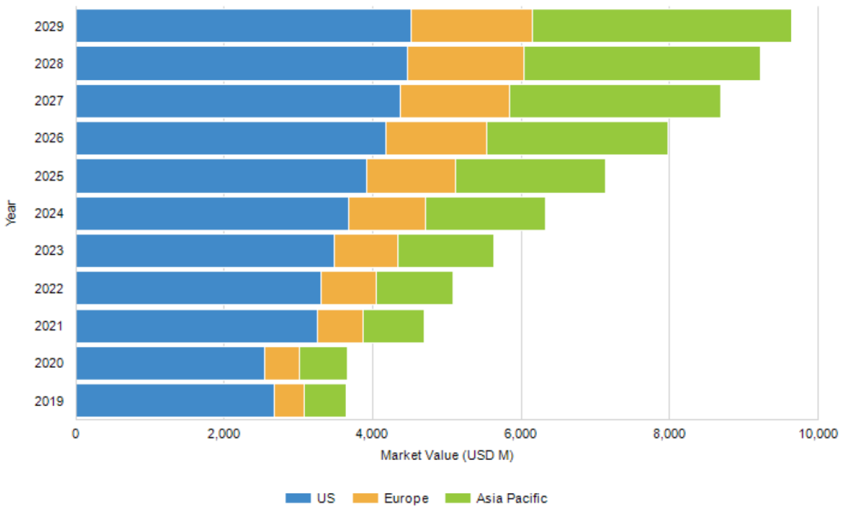

Figure 6.11 – Laparoscopic surgical robotic device market, by region, 2019-2029 [96]

6.6 Discussion

Haptic feedback is uncommon to see in the medical field especially in minimally invasive surgeries due to the reliance on the image modalities which can be sufficient in most cases. However, the image modalities can be complemented with haptics to operate with full safety and efficiency. Therefore, haptic features can have a great potential to fill that gap between experts and novices to enhance the learning curve. The step of commercializing technology with haptic features in the medical field is very slow compared to other applications due to the high cost of the current haptic devices such as Omega-x and others. Moreover, the physicians are reluctant to change the conventional procedures and to share the responsibility of a human’s life with a robot. Also, the nature of teleoperated systems with kinesthetic feedback is the stability and transparency issues to operate in a safe and effective way. Therefore, engineers need to improve the usability of the high-tech features as much as possible to suit the needs of physicians. This is crucial to demonstrate the added value of these features, such as the improvement in performance and reduction of cognitive overload during surgeries.

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