# Eye Gaze Tracking in Robot-Assisted Minimally Invasive Surgery: A Systematic Review of Recent Advances and Applications

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*Abstract: This article provides insights into the utilization of eye gaze tracking technologies in robot-assisted minimally invasive surgery. Ranging from enhancing surgical precision to non-technical skill assessment, workload analysis and extended reality-based applications, all recent research fields are covered. Utilizing the PRISMA methodology, relevant studies were identified, screened and analyzed from the past 5 years from PubMed and IEEE Xplore databases. This review reveals that eye gaze tracking technology can significantly improve surgical efficiency, reduce cognitive load reliably, assess skill and stress levels, and foster better coordination. In conclusion, eye gaze tracking is still a widely researched and evolving field in RAMIS, potentially revolutionizing surgical practices and patient outcomes.*

*Keywords: Eye Gaze Tracking, Surgical Robotics, Skill Assessment, Situation Awareness, RAMIS, Stress Measurement, Attention Computing*

# 1 Background

## 1.1 Robot-Assisted Surgery

Minimally Invasive Surgery (MIS) marks a revolutionary advancement in surgical procedures, fundamentally shifting the paradigm from traditional open surgery to methods that reduce tissue damage, recovery times, and lower the risk of complications. The genesis of MIS can be traced back to the early 20$^{th}$ century, evolving significantly with the technological advancements of digital medical devices [1]. The fundamentum of MIS is the use of small incisions, miniature cameras, and precise instrumentation, allowing surgeons to perform complex procedures with enhanced precision and minimal patient trauma [2].

The advent of Robot-Assisted Minimally Invasive Surgery (RAMIS) further augmented the capabilities of MIS. Emerging in the late 20th century, RAMIS integrates robotic technology with MIS, allowing surgeons to operate with unprecedented precision, flexibility and control. The RAMIS configurations, equipped with 3D vision systems and precision instruments empower surgeons to perform delicate and complex procedures with enhanced dexterity at a higher level of comfort. The advantages of RAMIS over traditional MIS include improved surgical accuracy, reduced surgeon fatigue and the potential for greater surgical (or sustainability) innovation through technology integration [3–5].

As RAMIS continues to evolve, there is an increasing emphasis on integrating more advanced technologies to enhance surgical performance and patient outcomes [6]. One such technological advancement is the incorporation of eye gaze tracking. Eye gaze tracking, originally utilized in psychology and marketing, has found significant applications in the surgical context, particularly in enhancing the understanding and capabilities of RAMIS [7].

The importance of eye gaze tracking in the context of a surgeon's skill assessment is profound. In both laparoscopic and robot-assisted surgeries, the surgeon's eye movements offer important insights into his cognitive state, decision-making process, and correlations to technical proficiency [8]. Analyzing gaze patterns and/or pupil metrics can help in identifying skill levels, optimizing training methodologies and even predicting surgical outcomes [9]. Furthermore, eye-tracking can contribute to presence and attention tracking, sanity and sobriety control and cognitive adequacy testing as well.

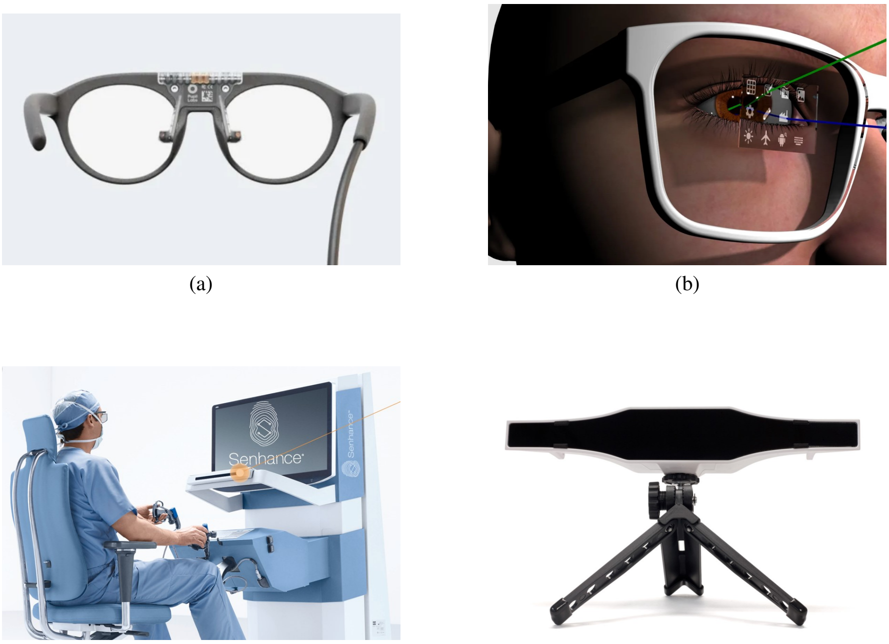
Furthermore, eye gaze tracking technology has promising applications as an input mechanism for autonomous surgical systems as well [10]. By tracking the surgeon's gaze, robotic systems can potentially anticipate the surgeon's needs, adjust camera angles, or even control instruments, creating a more intuitive and efficient surgical environment [11].

Additionally, eye gaze tracking holds potential in improving communication either in the Operating Room (OR) among the OR staff, or during training sessions. In the high-stress, demanding environment of the surgical site, non-verbal cues, such as eye movements or the point of gaze can be crucial for communication enhancement, coordinating tasks, intention indication, situation awareness and improving teamwork and safety [12–14].

This review paper aims to delve into the role of eye gaze tracking in RAMIS, exploring its integration, utilization in real surgical scenarios, and its potential as a tool for skill assessment and tool for enhancing communication. As the landscape of RAMIS continues to evolve, understanding and leveraging eye gaze tracking technology could be pivotal in driving forward the next generation of surgical innovation.

## 1.2 Eye-Tracker Hardware Types

eye-tracking is an established field, new types of eye-tracking hardware are being developed for general or surgical applications every year. In this subsection the main types of eye-tracking hardware are presented that can be used in RAMIS. Eye gaze




(a) (b) (c) (d)

Figure 1
Examples of different eye-tracking hardware types: (a) Typical head-mounted eye-tracker, the Pupil Labs Neon [15]. (b) Eyefluence's concept of gaze tracking for AR Glasses [16]. (c) The Senhance Surgical System with integrated eye-tracker for camera control [17]. (d) Typical remote eye-tracker, the GP3 from GazePoint [18]. (Images: curtesy of the manufacturer)

tracking hardware can be categorized into two types: remote and head-mounted devices. Remote eye-trackers can be used in a fixed space, they are often embedded in computer screens or set up stationary in environments, while head-mounted trackers are wearable devices, sometimes also called "eye-tracking glasses", that move with the head and can be used in various environments [19].

#### 1.2.1 Head-Mounted Eye-Trackers

Head-mounted eye-trackers (HMET) have the highest impact and potential in the field of RAMIS. They are wearable devices that often come in the form of glasses or a headband (Fig. 1a). These trackers are equipped with cameras and/or infrared sensors that capture eye movements. The older products rely on classical image processing methods, however, the latest products mostly build on AI-based eye and pupil recognition using pre-trained image processing models and deep neural networks (DNN) [20]. A key advantage is their mobility since they are often wireless, which allows surgeons to move freely during the procedures. Furthermore, most RAMIS systems are designed for being used even with regular glasses, thus such hardware is compatible with HMET as well by design.

This type of eye-tracking is particularly useful in robot-assisted surgery for tasks that require mobility and a wide field of vision, such as navigating surgical fields or selecting instruments. Widely used commercial examples include the Tobii Pro Glasses versions and the different models from Pupil Labs e.g., Pupil Core (relying on classical image processing algorithms) and Pupil Neon (built on AI-based image processing).

### 1.2.2 AR/VR Glasses

AR/VR (Augmented- and Virtual Reality) glasses are basically head-mounted devices often offering integrated eye-tracking features [21]. Strictly speaking, this makes them merely a sub-category of HMETs, however, due to the extensive research on the introduction of such devices in the operating room, they are worth to be discussed separately (Fig. 1b). In RAMIS, AR/VR glasses can be used for preoperative planning, real-time navigation and surgical training as well [22].

They allow surgeons to visualize complex anatomical structures, surgical plans and even real-time data overlayed in their normal field of view. Additionally, incorporating eye-tracking within these glasses enhances the interaction, enabling surgeons to control virtual interfaces or access information hands-free during the procedures, and most of these features can be enhanced by the integration of the eye-tracking data provided by the glasses as well. Most research activities aiming to integrate AR/VR glasses in the OR utilize the followings:

- HoloLens (AR, Microsoft, Redmond, Washington, United States),
- Vuzix M4000 (AR, Vuzix Corp., Rochester, New York, United States),
- Oculus Rift (VR, Microsoft, Redmond, Washington, United States),
- HTC Vive Pro (VR, HTC Corp., Taoyuan City, Taiwan)

### 1.2.3 Integrated Eye-Trackers

Integrated eye-trackers are built directly into the medical equipment, such as surgical microscopes or monitors. These systems provide seamless integration, offering the most intuitive and unobtrusive user experience for surgeons. On the other hand, thanks to their full integration, they can usually be used only for their pre-defined purpose, under stict regulatory conditions, and can not be utilized in different scenarios and novel research [23]. An example of this technology is the eye-tracking camera control system in the Senhance robotic system (Fig. 1c).

### 1.2.4 Remote Eye-Trackers

Remote eye-trackers are stationary devices placed at a distance, in front of the user, usually plugged into a computer or attached to a surgical console. They also rely on regular or infrared cameras and infrared light sources like HMETs to detect eye movements. These systems are highly effective in fixed scenarios when the subject is sitting stationary and looking at a monitor (Fig. 1d). This type can be used when a surgeon is operating with an open surgical console, however, the relatively large size of the device, and the required fixed position and free open space in front of the surgeon limit the applicability of such devices in RAMIS. Examples of remote eye-trackers include the SR Research EyeLink series and Gazepoint's GP3 eye-tracker.

## 1.3 Technology Utilization in Robot-Assisted Surgery

Each of the above-listed eye-tracking hardware types offers unique advantages for robotic surgery, enhancing the surgeon's interaction with the robotic system, improving precision and potentially reducing the cognitive load. The choice of eye-tracker depends on the specific requirements of the surgical procedure and the design of the robotic system.

In most fields of research, eye-tracking technology is used to evaluate psychological states, such as stress and cognitive load, and to monitor situational awareness. On the other hand, real-time eye-tracking can be used to enhance communication clarity as well, by letting the environment know what exactly the subject is looking at. This technique's ability to provide real-time, non-invasive insights into a person's focus, attention, and decision-making processes makes it an exceptional tool in many areas and research fields, ranging from psychology and neuroscience to human-computer interaction [24, 25].

In the context of RAMIS, eye gaze tracking has always been a popular research domain, offering unique insights into the surgical process, the surgeon's physiological signals, and their interaction with the robotic system [26]. The high-precision environment of RAMIS, where surgeons control robotic instruments within a human body, demands an exceptionally high level of concentration, spatial awareness, situation awareness, decision-making and many more skills, called "non-technical skills" [12]. Eye-tracking technology in this setting can be exploited in several ways:

1. **Surgeon Training and Skill Evaluation:** By analyzing the point of gaze of the surgeon at specific areas of the surgical field on the laparoscopic image, trainers can infer the surgeon's level of expertise. Several studies have already proved the connection between this metric and the skill level of the surgeons both in training and in real OR environments [12, 19, 27–29];

2. **Stress and Workload Assessment:** Some eye movement metrics are shown to be indicators of the surgeon's mental workload and stress levels. Unusual gaze patterns, such as too frequent shifting of the gaze or extremely prolonged fixation, might suggest confusion, fatigue, extreme stress, too high cognitive load, intoxication or other factors [27, 30, 31];

3. **Enhancing Surgical Precision and Control:** Eye gaze metrics can potentially be used to control certain aspects of the robotic system, such as the endoscopic camera arm movements of the da Vinci Robot, aligning the system's actions more closely with the surgeon's visual focus in an automated manner. This integration might lead to easier and more intuitive robot control, reducing cognitive load [32–35];

4. **Improving Communication:** Sharing the surgeon's gaze as visual information with the OR staff or a trainee can enhance communication and coordi-

nation during the procedure. For instance, knowing where the lead surgeon is looking can help assistants anticipate the next steps, improving the overall efficiency and speeding up the procedure [13, 36].

Despite its potential, the application of eye gaze tracking in RAMIS faces several obstacles. The primary challenge lies in seamlessly integrating this technology into the already complex environment of robotic surgery without adding to the visual and cognitive burden of the surgeon. The accuracy and reliability of eye-tracking systems in the dynamic, often visually cluttered surgical environment must be ensured to provide meaningful data.

Moreover, the interpretation of eye-tracking data in the context of surgery is not straightforward. The correlation between gaze patterns and surgical decision-making or skill level needs to be carefully established through extensive research. This involves not only technological development but also a deeper understanding of the cognitive processes underlying surgical tasks [37].

Current research directions mostly focus on improving the accuracy and robustness of eye-tracking systems in surgical settings, developing algorithms to meaningfully interpret gaze data in real-time, and exploring ways to integrate these data into RAMIS interfaces. The ultimate goal is to create a more intuitive, responsive and safer surgical environment, where technology seamlessly augments human skills and decision-making and/or assesses cognitive load and stress level.

As research progresses in this field, eye-tracking is expected to become an integral part of the next generation of RAMIS systems, further exploiting the fusion of human intuition and machine precision.

# 2 Methods

This systematic review aims to comprehensively explore and synthesize recent research on the utilization of eye gaze tracking in robot-assisted surgery. To ensure accuracy and transparency, the methodology adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, offering a structured approach for the collection, evaluation and synthesizing of findings from relevant studies in a methodical manner [1, 38].

Recognizing the expanding interest in this field, as evidenced by the significant increase in related publications in recent years (depicted in Fig. 2), this search was confined to high-end papers published in the last five years, meaning the 2018–2023 interval. This temporal delimitation was essential for being able to focus on current research actions and directions, rather than summarizing the past 20 years of the field, already provided in e.g., [25].

To manage the extensive scope of available information, only PubMed and IEEE Xplore databases were explored, circumventing the more general scientific publication databases due to their overwhelming volume of results, typically exhibiting a high variance in quality and scientific impact. For instance, the single search string

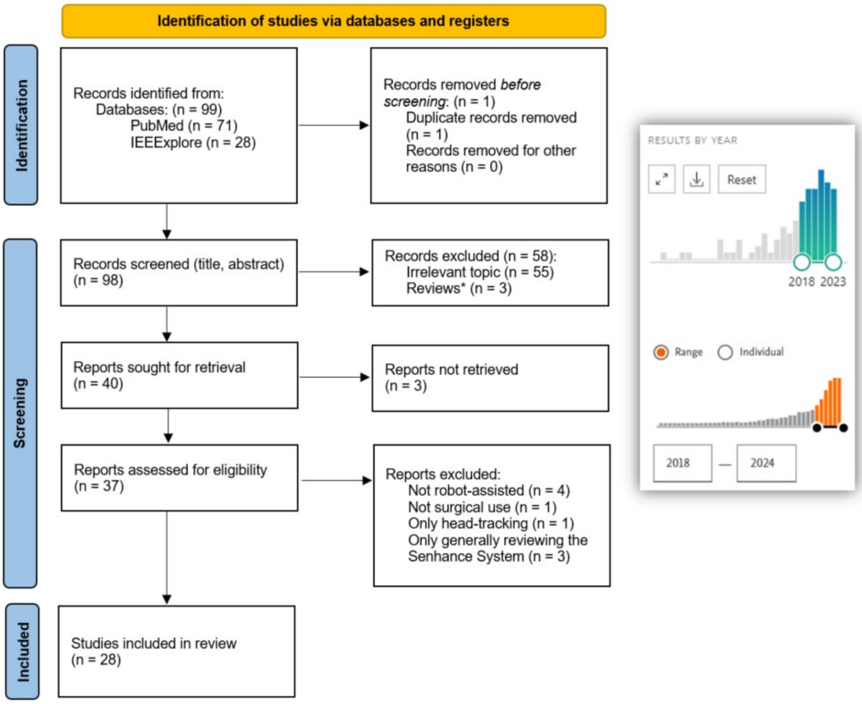



Figure 2
PRISMA Flow Chart of the conducted research, and the statistics of the number of identified papers each year in PubMed and IEEE Xplore databases respectively.

”eye-tracking” AND ”surgical robotics” in Google Scholar yielded approximately 17,500 results, reflecting the necessity for a more focused approach in the research methodology. The choice of the 2 databases was due to collating high-end publications while ensuring comprehensive coverage across both medical (PubMed) and engineering (IEEE Xplore) disciplines. These peer-reviewed databases are renowned for their strict selection of quality research in their disciplines, making them ideal for this review’s scope.

For paper search and identification, the advanced search option was used within the 2018–2023 time interval, ran December 2023. To identify the relevant papers, the following string was utilized: ((Eye track*) OR (Gaze track*)) AND ((Robot* Surg*) OR (Robot* assisted minimal* invasive surg*)), where ’AND’ and ’OR’ denote boolean operators, and the ’*’ sign is a wildcard symbol. The search term was designed to be inclusive yet specific enough, capturing studies that address eye gaze tracking utilized in any way in the field of robot-assisted minimally invasive surgery.

The outcome of the described database search is methodically represented in the PRISMA flow chart (Fig. 2). An initial pool of 99 studies was identified, with only a single duplication noted. The subsequent sections of this review will delve deeper into the analysis of the research, providing insights into the study selection process and the characteristics of the included studies.

# 3 Results and Discussion

We present the findings from the comprehensive screening of the papers that were identified and found to be relevant during preliminary screening (based on titles and abstracts). The screening was conducted by the predefined inclusion and exclusion criteria. The goal was to include all papers discussing eye gaze tracking in the context of RAMIS for any possible purpose. On the other hand, papers that were identified during the database-screenings, but – based on their abstracts – did not discuss clearly, only mention eye gaze tracking or did not cover any kind of robotic equipment related to surgical procedures were excluded. During this preliminary screening phase, most papers were excluded due to the following reasons:

- Covering robot-assisted eye surgery, not eye-tracking (n = 18);
- Covering hand-eye coordination (n = 16);
- Review articles (n = 10);
- Unrelated to surgery (n = 4).

During the full-text screening, 9 further papers were excluded from this study. The most common reasons for exclusion in this phase were:

- Not covering robotics, only regular or laparoscopic surgery (n = 4);
- Senhance Surgical System related paper, only mentioning, but not discussing its eye-tracking feature (n = 3).

The categorization of the reviewed papers based on the covered topic, type of employed eye-tracker, surgical system, qualification of subjects and the analyzed metrics are presented in Table 1.

The following subsections will detail the results of the review process based on the identified topics, outlining the main themes, methods and important findings from the screened and included 28 final publications. These results showcase the latest trends and developments in this field, while also highlight the directions of new advancements and possible gaps in the literature of this rapidly evolving research area.

Table 1
Summary of reviewed papers by different categorizations.
* Including papers about the Senhance Surgical System.
** da Vinci Surgical Simulator in most, but not all cases.
*** The subject-group with the highest training level included in the study.

| **Topic** | **Papers** | **Eye-tracker Type** | **Papers** |
|---|---|---|---|
| Extended Reality (XR) | [39, 40] | HMET | [13, 32, 36, 41–43] [9, 31, 44–46] |
| Gaze-controlled Robot * | [32, 41, 47–52] | Integrated | [53] |
| Skill Assessment | [9, 13, 42–44, 53, 54] | XR Glasses | [39, 40] |
| Stress Assessment | [13, 31, 42, 45, 46, 55] | Remote | [47, 50, 54, 55] |
| Other | [36] | Senhance Surg. Sys. | [48, 49] |
| | | RGB Camera | [51, 52] |

| **RAMIS System** | **Papers** | **Subjects *** ** | **Papers** |
|---|---|---|---|
| da Vinci Robot | [9, 44, 52] | Novices | [39, 40, 46, 51, 52, 55] |
| Surgical Simulator ** | [13, 31, 40, 42, 54] [45, 55] | Medical Students | [13, 31, 42] |
| Senhance S. S. | [48, 49] | Laparoscopic Surgeons | [32, 41, 43, 53] |
| Robotized Endoscope | [32, 47, 50, 52] | Robotic Surgeons | [9, 36, 44, 49] |
| Other | [41, 43, 51, 53] | | |

| **Eye-metrics** | **Papers** | **Validation Tools** | **Papers** |
|---|---|---|---|
| Gaze Pattern | [31, 43–45, 53, 54] | NASA-TLX | [31, 32, 41, 42, 45, 47, 55] |
| Pupil Diameter | [9, 31, 41, 42, 44, 45] | Other Likert Scales | [32, 41, 44] |
| Gaze Entropy | [9, 13, 31, 42, 44, 46] | Van der Laan Scale | [32, 41] |
| Fixation-related | [9, 13, 36, 41, 45, 46, 55] | EEG | [42, 44–46] |
| Task Time | [32, 36, 40, 41, 47, 48, 55] | | |

## 3.1 Gaze-controlled surgical robots

One of the most implicit utilizations of eye-tracking in RAMIS is the positioning of robotic arms, particularly gaze-based endoscope maneuvering. This application allows surgeons to control the movement of the endoscope (or, theoretically, any surgical tool or positioning robot arm) with their gaze or eye movements. This approach might provide a more intuitive and direct method of navigating the surgical field, and surgeons can focus more effectively on other critical aspects of the surgery, freeing their hands from this additional task. Integrating eye gaze-tracking as control signals with robotic systems marks a significant step forward in making complex surgeries more efficient, and aligns with the ongoing developments towards more advanced and responsive surgical tools and robotic systems.

During the screening of the recent publications, altogether 15 papers were identified as contributing to this topic. About half of these papers were related to the Senhance Surgical System (SSS, Asensus Surgical Inc., Durham, North Carolina, United States), as this is the first RAMIS system commercially implementing this technology. A separate subsection summarizes those publications. Most of the remaining papers utilized HMETs, exploiting their advantages of being lightweight, portable, precise and easy to fit to different scenarios. The rest of the papers used remote eye-trackers or regular RGB cameras with AI-powered eye gaze tracking, mostly in controlled, laboratory environments. Regular robot arms (UR, KUKA, Franka Emika) and the da Vinci Skill Simulator are the prevalent platforms for such developments, while subjects usually vary from novices to laparoscopic surgeons. Certified and experienced robotic surgeons were only found involved in studies with the SSS, revealing a serious but common deficiency in such research. Nearly all papers mention the long learning-curve associated with gaze-controlled robots in the OR, but on the other hand, most evaluation studies reported improvements in at least some of the following measured metrics:

- NASA-TLX for subjective cognitive workload assessment [56];
- Likert scale for ergonomics and usability [57];
- Van der Laan scale for technology acceptance [58];
- Task completion time;
- Other task-specific metrics.

Predominantly eye gaze tracking as a control signal in RAMIS – like in the SSS – is used to maneuver the endoscope. The majority of the studies developed and/or examined this type of robotized system, naturally comparing them to the classical way of positioning the endoscope by hand [32, 47, 50]. A common result is that the acceptance and usability indexes of the gaze-controlled endoscope were better within the novice and medical student groups, and less popular within professional endoscopists [32, 47, 49].

However, recent studies are more innovative than using eye gaze tracking only to maneuver the endoscope. Ezzat et al. in [41] built a "robotic scrub nurse" that handles the tool-tray in the OR based on the surgeon's gaze, which was reported to be promising direction but a little cumbersome for the surgeons, however, the human nurses liked the extra help. Two more papers in the topic were identified, in which Guo et al. and Li et al. present studies about AI-driven eye-tracking systems with regular RGB cameras as low-cost solutions developed directly for specific positioning tasks in the OR [51, 52].

## 3.2 Senchance Surgical System

During the initial screening phase of the review, it was revealed that many papers within the "Gaze-controlled surgical robots" category discuss the Senhance Surgical System, thus these papers were classified into a new subcategory. Although the SSS model involving eye-tracking got its FDA clearance in 2020, no study was found that directly examines the gaze-tracking-based camera control functionality.

Activated through button controls, the eye-tracking system enables surgeons to manipulate the SSS's camera's movement effortlessly without their hands, using only their eye- and head movements. As shown in Fig. 1c, the surgeon is looking at a monitor from a distance, while an integrated remote eye- and face-tracker detects his or her head and eye movements. After the initial calibration process, the endoscopic camera can be controlled by moving the gaze up, down, left and right on the screen and the zoom adjustment is achieved through back-and-forth head movements [49].

Three of the full-text screened papers about the SSS were excluded from this review, as they only present general studies, small reviews, or case studies about the SSS for different surgical procedures, merely mentioning its eye-tracking functionality [17, 59, 60]. Only 2 studies delve deeper into the gaze-controlled endoscope manipulation feature of the SSS, both mentioning the need for adaptation to this new technology from the surgeons (i.e., a relatively long learning curve), but acknowledging the long-term potential of this method [48, 49]. Krebs et al. in their study about the use of SSS on small piglets even complained that the eye-tracking-based camera control produced too rapid movements and they experienced lagging when activating this feature [48]. Nevertheless, the SSS stands out within the category of gaze-controlled surgical robots, being the first on the world to integrate gaze tracking-based camera control in a commercial surgical robotic system [60].

## 3.3 Skill assessment and workload analysis

Eye gaze tracking for surgical skill assessment and workload and/or stress analysis represents a significant area in RAMIS research as well. This approach utilizes the long-known relationship between the surgeons' eye-related metrics and their level of expertise, cognitive load, and stress level during training or real procedures. Besides having the potential to objectively evaluate surgical skills, this approach also provides deeper understanding of fatigue and stress in the OR. Modern eye-trackers offer numerous metrics related to the eye movements, including simple static attributes like pupil diameter, through dynamic and even statistical metrics like saccade or gaze entropy.

The gaze-related metrics that were predominantly found to be correlated with surgical skill level are mostly derived from gaze pattern i.e., where the subject is looking at the screen showing the endoscopic video or the simulated task:

- Gaze position relative to task location;
- Fixation-related attributes: duration, number, distribution;
- Saccade duration;
- Saccade to fixation ratio (SF-ratio);
- Rate of gaze change.

Most of these metrics are related to the different types of movements of the eyes, usually recorded by HMETs ($\sim$70%) or remote eye-trackers ($\sim$20%) in the studies. Fixation means that the gaze is focused on a certain (small) region of the field of vision, while saccade denotes the scanning, rapidly moving behaviour of the eyes. It is well known (from other fields, like aviation as well), that more fixation during task completion (i.e., lower saccade to fixation ratio) indicates confidence and a higher skill level. This was statistically evincible in many of the screened publications [9, 42–44], usually tested against NASA-TLX, task-scores generated by simulators, or validated clinical manual assessment tools like GEARS, GOALS, OSATS, etc.

In other papers, this assumption was already used for evaluation of different developments e.g., tool wrist length optimization by Miura et al. [54], microsurgery tool detection algorithm by Koskinen et al. [53], adaptive tool movement damping assistance by Nassar et al. [55], or semi-autonomous blood-suction by Barragan et al. [45].

Eye gaze tracking has been connected to skill assessment in various fields for decades, however, the correlation between some eye-related metrics and workload or stress level is a more recent research area. Alongside the technical skill-set of surgeons, non-technical skills are now getting recognized as essential in surgery as well [61]. Consequently, the methods for their direct and indirect assessments have become increasingly important, and eye-related metrics offer a promising direction [62]. Several of the screened papers utilized eye-trackers in their RAMIS research for workload assessment, sometimes even combined with eye-tracking-based skill assessment or automated endoscope-manipulation.

The classic way of workload analysis led through the filling of NASA-TLX (or other self-assessment tools), but data-driven approaches emerged in surgery too, hence researchers started to employ eye-tracking, EEG and heart rate measurements for workload assessment [63]. Many papers report a correlation between some eye-tracking metrics and stress-level or workload, which is usually measured or estimated by other, more conventional methods (e.g., EEG, HRV, NASA-TLX, or simply by the design of different tasks). The following metrics were found to be correlated to stress most frequently:

- Gaze entropy (an index that measures visual scanning randomness);
- Pupil diameter;
- Fixation-related metrics (mostly SF-ratio).

Gaze entropy and SF-ratio are calculated and provided by most eye-tracker devices.

It is worth mentioning that an increasing number of researchers employ different kinds of machine learning techniques to handle and combine the huge number of data types, e.g., 6-8 different eye-related metrics, EEG-based metrics and HRV data. Related publications usually conclude that the trained model is capable of estimating the stress-level using all the available input data, however, it is difficult to tell in such cases which metrics were really useful for the model [31, 44–46].

### 3.4 Other applications

Other than the above-mentioned typical applications, the authors expected more papers covering XR technologies and communication enhancement. However, only 2–3 papers were found about these topics, identifying a gap in the recent literature (at least, regarding the explored databases).

There are many research papers about the utilization of XR (eXtended Reality) technologies, primarily AR (Augmented Reality) in RAMIS ranging from preoperative planning to intraoperative phase in the OR [21, 22]. However, few applications exploit the eye-tracking capabilities of the AR/VR glasses. Among the identified papers, only 3 covered this topic, however, they proposed truly novel applications.

Melnyk et al. in [13] and Felinska et al. in [64] examined whether robotic surgery performance can be improved by showing the expert's gaze point to the trainees beside verbal instructions. eye-tracking related metrics were also examined for evaluation and both papers concluded that expert gaze guidance was indeed more effective than the regular training. Furthermore, Gras et al. in [40] proposed a system that could help the surgeons with the processing of the huge amount of extra information overlayed onto the surgical field by AR technology. This system toggled the AR layer (or parts of it) on and off based on the gaze tracking of the surgeon, resulting in better situation awareness in a simulated environment.

Other identified unique applications of eye-tracking in RAMIS – not fitting any of the aforementioned popular categories – were the followings:

- Decision making analyses during pre-operative planning [36];
- Iris tracking technology for robotic surgery [39];
- Validation for microsurgery tool-detecting algorithm [53];
- Wrist length optimization of a laparoscopic tool based on gaze-pattern [54].

## Conclusions

This paper presented a systematic review about the versatile applications of eye gaze tracking in robot-assisted minimally invasive surgery, highlighting its impact across various domains. From the pioneering first commercial integration in the Senhance Surgical System as an alternative camera control method, to its pivotal role in surgical skill assessment and workload analysis, the importance of eye gaze tracking is steadily growing. Thanks to the rapidly evolving hardware-pool, this technology not only augments surgical precision while disencumbering surgeons, but also offers important insight into the qualifications, stress-level, and workload of the surgeons. The continued evolution and integration of eye gaze tracking technologies in RAMIS promise to further improve human–robot interaction, and offer a deeper understanding of the human factor in surgery, potentially improving both patient outcomes and the comfort of the surgeons as well.

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## Abbreviations

The following abbreviations are used in this article:

| | |
|---|---|
| AR | Augmented Reality |
| DNN | Deep Neural Network |
| FDA | (U.S.) Food and Drug Administration |
| GEARS | Global Evaluative Assessment of Robotic Skills |
| GOALS | Global Operative Assessment of Laparoscopic Skills |
| HMET | Head-Mounted Eye-Tracker |
| HRV | Heart Rate Variability |
| MIS | Minimally Invasive Surgery |
| NASA-TLX | National Aeronautics and Space Administration Task Load Index |
| OR | Operating Room |
| OSATS | Objective Structured Assessment of Technical Skill |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| RAMIS | Robot-Assisted Minimally Invasive Surgery |
| SF-ration | Saccade to fixation ratio |
| SSS | Senhance Surgical System |
| VR | Virtual Reality |
| XR | Extended Reality |

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