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Surgical robotics:
current design, user experience, and potential for disruption.

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20-line summary:

Robotic-assisted surgery (RAS) has been developed over the last 40 years to allow the completion of complex surgical tasks through minimally invasive surgical access. There are 3 general surgical robots commercialized to date. The former monopoly Intuitive Da Vinci® system and the recent competitors CMR Versius® and Medtronic Hugo® have adopted the same architecture, where the robot is in fact a telemanipulator positioned on the surgical field, remotely controlled by a surgeon seating at a console allowing visualization of the surgical field and telemanipulation of the instruments. However, all available systems results in complex architectures lacking flexibility regarding robot accessibility and utilization, and cleverness regarding surgical planning and technique. A dominant design has not been reached, and users experience varies greatly according to the complexity of the surgery and the experience of the surgical team. There is thus plenty of room for incremental improvement or disruption using most advanced technologies: system architecture can be simplified, the number of components could be reduced from 3 to 2, lighter surgeon console could improve communication with the team, more intuitive actuator could reduce the learning curve, improved camera and imaging software could facilitate intraoperative navigation, and soft and flexible robotic arms and robotic ports would improve surgical dexterity while decreasing postoperative pain. A surgical robot could also benefit from improved in-room connectivity and decreased latency using 5G network. A cloud-based database including data from the robot and video from the surgical field would allow surgeons to teach and share, while robot manufacturer and regulatory agencies could track the safety and efficacy of the robot. This analysis thus identify the field of surgical robotics as a field of both incremental improvement and disruption that might be developed through simpler and smarter machines.
**Introduction**

The goal of a surgical procedure is to perform a complex task inside the body of a patient in order to treat a disease. Surgery was historically performed through large incisions so that the surgeon uses his native 3D vision and the 7 degrees of freedom of his hands (Loulmet, 1999). However, these open approaches lead to parietal damage, postoperative pain, and potential complications, and most surgeries are now performed through less invasive approaches.

The first mini-invasive surgical approach was Video-Assisted Surgery (VAS) or “keyhole surgery”, including laparoscopy in the abdomen (Lourenco, 2008) and thoracoscopy in the thorax (Sihoe, 2020). VAS is mostly based on the use of a camera, thus allowing the surgeon to visualize a magnification of the internal surgical field on an external screen. The surgical instruments (forceps, scissors, etc) have been roughly adapted but their ergonomics and functions remain basic. The use of long and non-articulated instruments through limited skin incisions decreases surgical precision, and the use of a mobile 2D camera is associated with visual limitations that hamper the quality of the gesture. Simple procedures can be performed through VAS, but complicated procedures usually cannot.

To overcome these limitations, Robotic-Assisted Surgery (RAS) has been developed over the last 40 years in two distinct directions. Task-specific surgical robots are now capable to perform a simple task according to patient-specific imaging with some kind of automation, like making a biopsy of a tumor or guiding the insertion of an orthopedic prosthesis. General surgical robots allow the telemanipulation of reduced-sized and increased-mobility surgical instruments inside a body cavity, but do not show any kind of automation or patient-specific programming (Satava, 2002). However, general surgical robots allow the achievement of complex surgical tasks through a minimally invasive access, they have been widely adopted by the surgical community, and they will be the focus of the following analysis.

Since the year 2000, the most used general surgical robot is the Da Vinci® system (Intuitive Surgical, Sunnyvale, CA). About 6,000 systems are currently used in 67 countries, and more than 8.5 millions surgical procedures have been performed over the last 20 years. The Da Vinci® system underwent incremental improvement in imaging and ergonomics, but it remains globally consistent with its original design. After 20 years of monopoly, this system has only recently been challenged by concurrent systems commercialized by the English start-up CMR (Versius®, Cambridge Medical Robotics Surgical, Cambridge, UK) and the multinational Medtronic (Hugo®, Medtronic, Minneapolis, MN, USA). These recent competitors are designed according to the same global architecture (Bravi, 2022; Kelkar, 2022).

Existing general surgical robots have thus been characterized by incremental evolution leading to a current design with no apparent disruptor in the very last years, despite abundant technical progress in the field of robotics, electronics and image display. It therefore appears of particular interest to decipher the current design of a general surgical robot, to analyze user experience, and to screen technological solutions that might lead to disruptive innovations in the forthcoming years.
1. Current design

a. Product development

For 20 years, Da Vinci® has been the only general surgical robot commercially available (Pugin, 2011). In 1999, the first version of the Da Vinci® system included a surgeon console with 2 master commands and a 3D binocular display, linked through optical connections to a vision cart allowing the team to see the operative field, and to a patient cart that supported 3 robotic arms. The surgeon is seated at a console looking at 3D glasses showing the surgical field and manipulating instrument controllers; the telemanipulated instruments are articulated at their distal tip to reproduce the movements of surgeon's hands, including its 7 degrees of freedom (Loulmet, 1999). The surgeon console is placed in the operating room, a few meters away from the patient. Therefore, after inserting the trocars trough the abdominal or thoracic wall, docking the robotic arms to the trocars, and inserting the robotics instruments inside the cavity up to the surgical field, the surgeon can take off gown and gloves and operate in surgical scrubs during the robotic phase of the procedure.

In 2002, the next version of the Da Vinci® system include a 4th arm to retract anatomical structure and favor surgical exposure during the procedure. In 2009, the Da Vinci® model Si was associated with improved mobility of the robotic arms and greater ergonomics that favor the docking of robot positioning and surgeon dexterity. This model also included a second surgical console that allow surgical mentoring during the procedure. Introduced in 2014, the Da Vinci® model X include the possibility to switch the camera from one arm to the other, it also include a near infrared camera to improve the anatomical visualization of tumors and blood vessels after injection of a fluorescent dye, and it embed new instrument that improve surgical hemostasis, tissue sealing, and tissue stapling. Available since 2018, the Da Vinci® model Xi is the latest version available. It exhibits improved cart rotation and arm motions allowing larger field of action, and a coupling of the robot with the operating table to modify patient’s position while the robotic instruments are on the surgical field. To date, the Da Vinci® system remains a strictly passive robotic assistance. The prices of the latest versions range from 0.8 to 1.5 Millions Euros.

b. Current system architecture

As a consequence of history, the design of the surgical robot adopted during the 1990s was not optimized for minimally invasive surgery, but rather for open surgery in specific circumstances, where the surgeon cannot access to the patient (battlefield) or could gain dexterity to perform ultra-precise task (micro surgery). Even though the design has been incrementally upgraded, the design of the Da Vinci® system remained relatively stable over the years, and has been only partially modified by the recent competitors.
System architecture. Surgical robots are passive systems based on a master-slave relationship. The usual set up of surgical robotic systems includes a master unit or surgeon console, a vision cart or tower with a screen showing the surgical field, and a patient cart with a limited number of actionable remote-controlled robotic arms. The system provides the surgeon with a controller that is directly in the surgeon’s hand, and the surgeon interacts with the robot by displacing this controller (Anderson, 2016).

Figure 1. Architecture of the Da Vinci® system with the surgeon seating at the console.

Surgeon console. The console is composed of two hand controllers that control the robotic arms, a computer, and a 3D display that mimic stationary 3D glasses placed above the hand controllers. The surgeon is seating on a stool with the elbow on a support, each hand on a master control, and the head on the 3D imaging system. An infrared sensor detects when the surgeon’s head is placed into the console and triggers activation of the two master controls (Kalan, 2010). These master controls manipulate the arms of the robot after alteration by the computer to compensate for difference of speed and displacement between the command and the instrument. Interestingly, the Da Vinci system does not provide haptic feedback, so the surgeon cannot feel the tension of the tissue with his hand, but it can provide visual feedback, as the surgeon can infer the tension of the tissue from the image.
Patient cart. With 800kg per meter square, the patient cart is the heaviest module of the Da Vinci® system. It has four arms, one for the camera and three for surgical instruments. The arms are attached to operative trocars placed though the thoracic or abdominal wall of the patient. The surgical instruments have a diameter of 8mm and a total length of 55cm, they are connected to the robot proximally, and then inserted through the trocar down to the surgical field. The instruments are stiff, and so is the 8mm trocar that cross the abdominal or chest wall to enter the cavity. The tip of the instrument is articulated with 7 degrees of freedom and 2 degrees of axial rotation, imitating the human wrist. The articulation of the wrist is obtained through four Bowden wires and distal pulleys that control a rotatable shaft and the specialized instrument placed at the tip. The da Vinci® system monitors a location near the instrument tip, so that instrument can be changed and the new instrument get to the position of the previous one.
**Imaging system.** The da Vinci® system has a binocular endoscopic vision for the surgeon console. Two cameras are placed inside the 8-mm telescope, and the images are projected on two screens that are synchronized to create a single binocular view of the surgery (Kalan, 2010).

*Figure 4. Da Vinci® vision system.*

**Vision cart.** A vision cart or tower is placed near to the patient, with a screen displaying images from the scope in 2D, and giving feedback about the state of the system, the instruments inserted, and any error messages. The vision cart is important for the surgeon during the non-robotic phase of the surgery, including trocars insertion and withdrawal, and for the surgical team in charge of changing instruments when the surgeon is at the console during the robotic phase of the surgery. The energy sources that are connected to the surgical instruments in order to coagulate or seal tissue on the surgical field are also in the tower. The vision cart can be upgraded with a recorder to give track of the whole surgery.

*Figure 5. Da Vinci® vision cart.*
Connections. Connections between system elements are made through optical fiber, that run through the operating room from one element to another. Even though most systems are now set in a dedicated operating room, the Da Vinci® system can exceptionally be moved from one operating room to another, so these optical fibers are not integrated in the operating room, they just lay on the ground. The system is also connected via internet to a dedicated customer portal that keep track of instruments uses, surgical times, and system errors, but is not able to record live surgery or to send instantaneous recommendations to the surgical team.

c. Recent competitors

CMR Versius. The Versius® system is designed as a modular platform for a broad range of soft-tissue procedures. The Versius® system has been approved for urologic, gynecologic and abdominal procedures in Europe in 2019, and the first human procedures have been performed the same year (Kelkar, 2021; Kelkar, 2022). Interestingly, the development of the Versius system has been very linear, from end-user feedback to optimize the design of the robot (Hares, 2019) to preclinical (Morton, 2021) and then prospective clinical studies (Kelkar, 2021; Kelkar, 2022) with peer-reviewed international publications all along the process. In France, the price of the Versius® system is around 1.5 Millions Euros, comparable to the price of the Da Vinci® system. End-user feedback led to a mobile design with independent arm carts linked by serial or parallel connections, with the ultimate goal to provide flexibility in the operating room (Wehrmann, 2022). If the system architecture remains similar to Da Vinci®, the main difference between both systems include:

- Surgeon console: images from the surgical camera are displayed on an open screen with the surgeon and his team wearing 3D glasses. The position of the surgeon is therefore with the head up, easing communication with the team, and allowing the surgeon to stand.

- Patient cart: the 4 arms of the system are separated in 4 individual 80-kg carts than can be arranged around the patient. The system can be easily limited to one, two, or three arms, leading to a reduction in the space occupied by the robot around the surgical field. The conception of the arm is inspired by the human arm, with an external shoulder, an external elbow, and an internal wrist. The instruments and trocars are stiff.

- Vision cart: the tower is placed close to the patient carries a 3D screen so that the surgical assistant can benefit from the 3D vision of the surgical field. The type of energy provided for hemostasis and tissue sealing is also different from the Da Vinci system.

- Connections: the system is connected with a user portal to check system utilization, but it can also be connected to a surgeon portal to record the surgery performed, keep track of the videos, and edit them for didactic purposes.
Figure 6. Architecture of the Versius® system.

Figure 7. Focus on the Versius® robotic arm mimicking human arm.
Medtronic Hugo RAS. The Hugo® system is also defined as a modular platform designed for soft-tissue procedures. The Hugo® system has been approved for urologic and gynecologic procedures in the USA and in Europe in 2021, and the first human procedures have been performed in the very last months (Bravi, 2022). Even though the prices are not publicly available, it is claimed by the Medtronic company (Medtronic, Minneapolis, MN, USA) to be cheaper than the Da Vinci® system, and to be easier to move from one operating room to another. It combines wristed instruments, 3D visualization, and a cloud-based system designed to allow surgical video capture and management. If the system architecture remains similar to Da Vinci, with some differences that place the Hugo® close to the Versius® system:

- Surgeon console: images from the surgical camera are displayed on an open screen with the surgeon and his team wearing 3D glasses;

- Patient cart: the 4 arms of the system are separated in 4 individual carts than can be arranged around the patient. The system can be easily limited to one, two, or three arms. As compared to Versius®, the volume of the carts is more important and might hinder the access to the patient.

- Vision cart: the tower placed close to the patient carries a 3D screen so that the surgical assistant can benefit from the 3D vision of the surgical field. The type of energy provided for hemostasis and tissue sealing is also different from the Da Vinci® system;

- Connections: the system is connected with a user portal to check system utilization, but it can also be connected to a surgeon portal to record the surgery performed, keep track of the videos, and edit them for didactic purposes.

Figure 8. Architecture of the Hugo® system.
**d. Dominant design**

**Definition.** A dominant design is defined as a specific path along a design hierarchy, which establishes primacy among competing design paths. Dominant design shift the terms of competition in an industry (Abernathy, 1978). Interestingly, the dominant design is not necessarily the result solely of technical potentials, but also of timing and collateral assets. In several industries the dominant design have not yet occurred (Suarez, 1993).

**Pros.** Considering the common architecture of the former monopoly Intuitive and the two newcomers CMR and Medtronic, it could be possible to consider that a dominant design for general surgical robot has been reached, characterized by:

- a passive electromechanical device working on a master-slave relationship,
- a surgeon console that allows 3D visualization of the surgical field and action on specific handgrips,
- a patient cart that deploy arms equipped with remotely controlled stiff instruments including distal articulations.

The achievement of a dominant design might be supported by the lack of investment of surgical robotics firms in disruptive technologies, and their growing investments in process innovations including the improvement of patient path in the hospital and in the surgical suite, or the addition of companion technologies including 3D reconstruction of preoperative CT scan, patient specific surgical planning, and cloud-based surgical video capture and management solution.
Cons. However, to date robotic surgery account for less than 3% of all the surgeries performed worldwide, and less than 10% of all the minimally invasive surgeries performed in developed countries (Marcus, 2017). Furthermore, current general robotic systems are limited to stiff electromechanical devices without haptic feedback, task automation, or image guidance. The placement of a general surgical robot into the operating room has also been characterized by significant changes in the dynamic of the work-system that might erect barriers to safety and efficiency (Kanji, 2021). Major technical innovations are thus possible, and major changes will probably be achieved in the forthcoming years. It is not possible to predict whether these changes will be important enough to challenge the current design and to set the dominance of a new design.

Path to innovation. Once a degree of standardization is accepted, major innovations seem less and less likely to occur in an industry. Further innovation can be fostered through different ways, including a wave of new entrants and increasing competition, or the willingness of the firms to open new strategies related to their core technology and its evolution (Utterback, 1975). Further innovation can have different goals: to be the first to introduce technically advanced products, to watch others innovate while being prepared to introduce new product features, or to enter the market later in the product life cycle with simpler versions. In all cases, a degree of experimentation and a rich collaboration between producers and users is required for a design to be dominant (Utterback, 1975; Suarez, 1993).
2. User experience

a. End-users needs

To analyze the expected changes in the field of surgical robotics, it therefore seems of major importance to study the end-users experience. The end-user of a general surgical robot can be the patient or the surgeon. From the patient perspective, the main goal of the surgery is to have a condition cured with a predictable postoperative course, i.e. without intraoperative or postoperative complications, and without adverse consequences on health-related quality of life, i.e. without significant pain or disability. From the surgeon’s perspective, the ultimate goal of the surgery superimposes patient’s perspective, with the addition of intermediate needs that include the feasibility and reproducibility of the technique as part of a complex process of care beginning with diagnosis and ending with postoperative recovery. Most clinical studies have found RAS to be associated with reduced blood loss, postoperative complications, hospital length of stay, and postoperative pain (Marcus, 2017). However, the global uptake of RAS remains below 10% of all the minimally invasive surgeries performed in developed countries, suggesting there are barriers to its use (Hares, 2019). Above the financial aspects that will not be discussed here, major barriers identified included ergonomics issues and flow disruption, safety and efficiency, and non-technical skills. These barriers are usually classified as technical aspects, including surgical skills, and non-technical aspects, including work-system dynamics (Kanji, 2021). We will also explore technological aspects that directly result from the history of the system and have now major impact on its utilization, even though these aspects are being underestimated by most studies.

b. Technical aspects

The surgical technique of a robotic procedure has been adapted from open and video-assisted procedures. It can be deciphered in 4 different phases. Phase 1 starts when the patient enters the OR (pre-robot); phase 2 begins once the first trocar is in place and includes robot docking; phase 3 starts once the surgeon is at the robotic console and includes the main surgical intervention; and phase 4 begins once the surgeon is off-console and includes robot undocking. All 4 phases have to be adapted from established VAS or open surgery protocols. After the onset of general anesthesia, the position of the patient on the operating table is different for robotic as compared to video-assisted or open surgery. Port placement and robot docking has been improved over the years, but it remains a complex phase with a lot of interruptions. The main surgical intervention has been adapted from open surgery, it is now safe, efficient, and highly reproducible, but it is affected by the technological limitations of the robot that will be developed below. Robot undocking is also at risk, as the coordination of robotic and non-robotic phases might be difficult. Overall, visual problems, including fogging or blood on the camera, are the most frequent problems. It requires removal, wiping, and re-insertion of the camera. The second most
frequent problems are collisions between the robot arms. Such problems result from an altered positioning of the arms, leading arms to strike one with another, and thus to limit the motion of both arms. It requires adaptation of the surgical technique, or removal of the surgical instrument and adaptation of the arm position. Inoperative robotic equipment, including those that for any reason could not be operated correctly, is also a common feature during robotic surgery. It usually requires the removal followed by reinitialization of the instruments, and less frequently the replacement of one instrument (Catchpole, 2018).

c. Dynamics of the work-system

The placement of a surgical robot into the surgical suite changes the way in which work is usually done. RAS implementation thus introduces many non-technical challenges with important performance implications (Kanji, 2021). The size of the robot itself and the complexity of its connections and placements is associated with layout issues. Particular challenges are founded in the organization of the room, the retrieval of supplies, the positioning the patient, and the maneuvers of the robot (Kanji, 2021). The docking process is significantly more disrupted than other procedural phases (Cofran, 2022). Then the position of the surgeon at the console, and the separation from the rest of the team necessitates changes in communication and teamwork. The architecture of the robotic system also increases the need for verbal communication which is already one of the most frequently cited causes or procedural error and surgical injury (Kanji, 2021). The development of non-technical skills adapted to this complex environment is an integral part of training (Sridhar, 2017).

Figure 11. Placement of the robot into the operating room emphasizing layout issues.
d. Technological aspects

The surgical technique of a robotic procedure has been adapted from open and video-assisted procedure to optimize the use of the robot, minimize the risk of complication, and allow reproducibility. It is therefore a compromise between what the surgeon would like to do, and what the robot can actually do. Most of the limitations to what the robot can actually do directly result from technological choices made 30 years ago when the robot was designed for distant open surgery. The size of the robot, the complexity of the connections, the difficulty to obtain a clear view of the surgical field, the position of the surgeon away from the patient and surgical team, the large ports and complex docking process, the stiff instruments with distal articulation, and the conflict between arms could be resolved through technological progress. In fact many startups companies have been founded to optimize the value-proposition of a general surgical robot. Few of them have clarified their technological choices. Some of them have changed their name, some others are not existing anymore. For clarity purposes, we have chosen to focus on startups that are recognized in the ecosystem, and cited in the MassDevice ranking “16 surgical robotics companies that you need to know” published on August 2022 (MassDevice, 2022). We have studied available data, mostly from their website, less frequently from published scientific articles. The above discussion is thus based on publicly available information at the time of writing.

Table 1. The MassDevice “16 surgical robotics companies that you need to know”.

<table>
<thead>
<tr>
<th>Company</th>
<th>Robotic systems</th>
<th>Field</th>
<th>Included in this analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intuitive Surgical</td>
<td>Da Vinci Xi, Da Vinci X, Da Vinci SP, Ion</td>
<td>General surgery</td>
<td>Yes</td>
</tr>
<tr>
<td>Medtronic</td>
<td>Hugo</td>
<td>General surgery</td>
<td>Yes</td>
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<tr>
<td>Johnson &amp; Johnson</td>
<td>Monarch</td>
<td>Task specific</td>
<td>Yes</td>
</tr>
<tr>
<td>Stryker</td>
<td>Mako</td>
<td>Task specific</td>
<td>No</td>
</tr>
<tr>
<td>Siemens Healthineers’ Corindus</td>
<td>CorPath GRX</td>
<td>Task specific</td>
<td>No</td>
</tr>
<tr>
<td>Vicarious Surgical</td>
<td>Beta 2</td>
<td>General surgery</td>
<td>Yes</td>
</tr>
<tr>
<td>Titan Medical</td>
<td>Enos</td>
<td>General surgery</td>
<td>Yes</td>
</tr>
<tr>
<td>Asensus Surgical</td>
<td>Senhance</td>
<td>General surgery</td>
<td>Yes</td>
</tr>
<tr>
<td>Moon Surgical</td>
<td>Maestro</td>
<td>General surgery</td>
<td>Yes</td>
</tr>
<tr>
<td>Momentus Surgical</td>
<td>Anovo</td>
<td>General surgery</td>
<td>Yes</td>
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<tr>
<td>Virtual Incision</td>
<td>MIRA</td>
<td>Task specific</td>
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<tr>
<td>Stereotaxis</td>
<td>Genesis RMN, Vdrive, Niobe</td>
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<td>Monteris Medical</td>
<td>NeuroBlate</td>
<td>Task specific</td>
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<td>Rosa</td>
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<td>EndoQuest</td>
<td>ELS</td>
<td>Task specific</td>
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</tr>
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</table>
3. Potential for disruption

**System conception.** Reduction in the size of electronic and electromechanical systems could lead to a significant downsizing of the robot. The 3 parts including surgeon console, patient cart and vision cart could be reduced to 2 parts, including surgeon console and patient cart. The command-control could be much smaller to be able to move it from the storage to one operating room or the other. The patient cart could also be smaller to facilitate the access of the team to the patient. These conceptions have been chosen by the newcomers Medtronic and CMR, and pushed further by startups including Asensus, Distal Motion, Titan, Momentis, Vicarious, and Moon surgical, from the largest to the smallest system according to publicly available information. Vicarious surgical has planned to pack the command control and patient cart in only one cart. Moon surgical has not planned to have a dedicated command control unit, but rather to integrate it to the patient cart while the surgeon is supposed to stay in the surgical field. The goal of size reduction is to integrate the robotic system inside the workflow of a surgical suite, thus increasing its utilization while minimizing flow disruption. Some of the systems in development allow the surgeon to remain close to the surgical field, and even on the surgical field in the case of Moon surgical, that pushes the concept of enhanced laparoscopy or permanent robotic assistance, for all surgeons and all surgeries.

*Figure 12. Architecture of the Vicarious® system.*
Surgeon console. The type of surgeon console is progressively moving from a closed console to an open console. The open console is supposed to favor interactions between the surgeon and the team, but it can also favor distractions from the outside world (phone, students, etc). The ergonomics of the actuators vary according to the system, from the classical forceps in the Intuitive system, to the pistol-like handgrip in the CMR and Senhance systems, and the gamer-like joystick in the Auris Monarch and Momentis system. Interestingly, Vicarious and Titan sought to set a natural multi-articulated handle interface. The interface between the surgeon and the robot could also benefit from the recent progress in haptic feedback gloves and peripheral nerve interface. Haptic feedback gloves are wearable devices that allow users to experience realistic touch and interactions through advanced tactile feedback. The most advanced haptic gloves combine microfluidic skin to provide true-contact haptics for realism, force-feedback exoskeleton with pneumatic actuators, and precise motion tracking that can be magnetic or optical. A peripheral nerve interface is a bridge between the peripheral nervous system and a computer interface recording and sending signals between the human body and a machine processor. Neuroprosthetic devices providing tactile feedback sensation have been recently developed, but their applications to the control of robot have not been reported to date (Vu, 2020). If peripheral nerve interface are at too early stage to discuss their implementation in the field of robotic surgery, the control of a surgical robot could certainly benefit from haptic gloves in the forthcoming years.
Patient cart. The robotic arms have a huge room for improvement. The arms of the Intuitive system have been designed 30 years ago, with mobile elements handling the instruments and sliding along long arms. The instruments are stiff and goes through stiff ports, their articulations are only distal. This technology is still reliable and has been chosen by the newcomer Medtronic. However, it is associated with important conflicts between arms, and between the arms and the abdominal or thoracic wall. CMR has developed articulated arms with external shoulder and elbow, and internal wrist instruments. The external conflicts could be reduced, but the instruments are still limited in rotation, stiff when they cross the trocars on the abdominal or thoracic wall, and internal conflicts do occur. Interestingly, some startups are developing flexible arms such as Momentis and Titan who both claim 360° flexibility for the tip of the instrument. The arms of the Vicarious system have 3 internal articulations but are not flexible. The Da Vinci® Single Port system will be commercialized worldwide very soon. It has also 2 flexible arms. Interestingly, this technology is also used for endoscopic robot to performed bronchoscopy, like the Intuitive Ion or the Auris Monarch system. As the bronchus are tortuous, the bronchoscope and sheath are associated in a telescoping design that
provides stability and adaptability. The sheath can be articulated up to 130 degrees in any direction to create a stable base to advance the small bronchoscope. Once advanced beyond the sheath, the bronchoscope provides an additional 180 degrees of flexion in any direction (Auris Health, 2022). Unfortunately, in general surgical robots such maneuverability is still not possible, and all the cases of flexibles arms are packed in a single port. Single port robotic systems access body cavity through a rigid 2.5cm diameter tube. Such configuration is associated with altered triangulation and might be associated with parietal damage for the patient. From a surgeon perspective, the idea of independent flexible arms coming through multiple flexible ports should be less invasive and more precise as compared to the single port configuration.

Figure 16. Flexibles arms.

Imaging system. Surgeon console is progressively moving from a closed console with immersive 3D glasses to an open console with a 3D screen and glasses for the surgeon and the team as offered by CMR, Medronic, Asensus, Distal Motion, Titan, Momentis, and Moon surgical. Virtual reality glasses are being developed by Vicarious surgical, but it might be isolated again the surgeon from the team. Interestingly, Augmented Reality glasses are not used at the moment, but could be an interesting perspective to display the information from the robot and the images from the surgical field, while the surgeon can still interact with the team. At the other end of the signal, the scope is holding 2 cameras.
to allow for 3D vision. The 2 cameras are only a few millimeters apart in all the systems offering stiff arms, but they can be combined in a face-like disposition in the systems offering flexible arms. The advantage of the placement of the cameras on a separated mobile module is the opening of the accessible field, from 180° with the classical disposition to 360° with the mobile module. Furthermore, Vicarious is developing Virtual Reality glasses with head motion tracking that could direct the camera according to the movements of the surgeon’s head. However, the surgeon might experience discomfort up to nausea if the movements of the camera are too wide or too brutal. Unfortunately, no company is currently addressing visual problems that include fogging, tissue or blood on the camera, and remain the main factor of interruption during robotic surgery. The creation of antifogging system, wiper and windscreen washer could be of particular interest in this setting.

Figure 17. Advantages of the mobile cameras in the Vicarious® system.

Computer. To date, general surgical robots are purely passive devices. It is possible to watch the 3D reconstruction performed from the preoperative medical images, including CT scan and MRI. The software could be commercialized by the robot manufacturer such as the Intuitive IRIS system, or commercialized by other companies such as the Fujifilm Synapse® software or the Visible Patient® system. In all the cases the 3D reconstruction is performed preoperatively, it is uploaded on a mobile device such as a smartphone or a tablet, and it is connected to the robot. These preoperative 3D reconstructions can be displayed next to the live images from the surgical field, but the superimposition of both is not possible, mostly due the deformation of the targeted organ, the motions of surrounding organs, the displacement of the diaphragm, and the beats of the heart. The use of preoperative reconstruction is associated with an improvement in the accuracy of the surgery, the
completeness of the resection, and the occurrence of postoperative complications, but is not specifically integrated in the general surgical robots to date (Chen, 2022). Among the developmental systems, Asensus is working on intraoperative perceptive real-time guidance through augmented intelligence, but has not disclosed any specifics on this subject. The superimposition of preoperative images to the surgical field would be an help for the surgeon, but most importantly, it is an essential prerequisite to the development of automated surgical robotic systems.

Figure 18. Preoperative 3D reconstruction of the organ and tumor (here, a tumor in the right upper lobe of the lung) and their inclusion on the robotic imaging display (here, the division of the mediastinal artery of the upper lobe of the lung).

Connections. The connections of the surgeon console to the patient cart should be fast and reliable. Humans can compensate for latency from the masters to the tip of the instrument of up to 200 milliseconds, after which the delay is too great for surgical accuracy (Satava, 2002). In the Da Vinci system, the connections are made of optical fibers, assuring for speed, but not for reliability. As the optic fiber are lying on the floor, it adds to the complexity of the system, the difficulty to move and dock the robot, and there is a risk for disconnection. 4G mobile network was not fast enough to ensure for accuracy, but 5G network might. 5G technology offers a low latency rate, that decreases from 200 milliseconds for 4G to 1 millisecond with 5G. A wireless 5G connection of the surgeon console to the patient cart would be of great interest to simplify the architecture of the system, improve safety, and improve end-user experience. Additionally, remote connection with the internet could help to record
videos and data from the surgery. Cloud-based solutions are now offered by Intuitive, CMR and Medtronic. The completeness of video and data gathering and the use of secured and intuitive recorders will be key to find use cases that may include educational purposes, safety survey, or quality improvement. The link with patient electronic record will also be important to analyze the outcome of interest for short term (in-hospital complications, in-hospital mortality) and long term study (overall survival, recurrence-free survival in case of cancer).
Conclusion – Limitations and perspectives

Limitations

Our study has some limitations. We have performed a bibliographic study from publicly available sources. As the field is very competitive, some technologies might have been kept secret for years, and by definition have not been included in this report. Similarly, there are currently a lot of startup companies addressing the pain points of surgical robotics, but only very few offer structured propositions and informative figures that allow to understand the underlying technology. Even the concretization of a functioning prototype is sometimes not very clear. We have chosen to focus on the commercially available systems, and on the most advanced startups company as high lightened by the surgical robotics ecosystem (Mass Device, 2022). The field of surgical robotics included task-specific surgical robots, general surgical robots, and most recently endoscopic robots. We have chosen to discuss general surgical robots and this discussion leads us to endoscopic robots, but task-specifics surgical robots also constitute a very interesting and very evolving field that could have been analyzed further. Lastly, our analysis that a dominant design has not been achieved in general surgical robot, and that further progress will come, either from incremental changes or from external disruption, is a personal analysis that can be challenged.

Perspectives

With respect to these limitations, it appears that despite 20 years of preclinical development and 20 years of clinical use, surgical robotics are still at a very early stage. In task-specific surgical robotics, the architecture of the device is devoted to a single task and has therefore been optimized. In general surgical robotics, the current architecture of the system cannot be qualified as a dominant design. The user experience is still limited by some technological choices that have been made decades ago. There is thus plenty of room for improvement in all the part of the system architecture, including lighter console design, use of haptic gloves or intuitive actuators, development of antifog and windscreen washer for the camera, superimposition of preoperative 3D imaging on the surgical field during the procedure, simplification of the system connections through 5G network, implementation of soft flexible arms operating through soft ports, and availability of a cloud based system to follow surgeon performance and system safety and efficacy. The development of small scale robotics, including but not limited to Microelectromechanical systems (MEMS), opens interesting perspectives but also raised enormous challenges before considering their clinical use.
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- https://www.aurishealth.com/procedure/bronchoscopy/features
- https://www.massdevice.com/16-surgical-robotics-companies-you-need-to-know/
ANNEXE 1 – Figures references

Figure 1. Architecture of the Da Vinci® system with the surgeon seating at the console.

Figure 2. Da Vinci® surgeon console.

Figure 3. Da Vinci® patient cart and articulated instruments.

Figure 4. Da Vinci® vision system.

Figure 5. Da Vinci® vision cart.

Figure 6. Architecture of the Versius® system.
https://cmrsurgical.com/versius/surgeon

Figure 7. Focus on the Versius® robotic arm mimicking human arm.
https://cmrsurgical.com/versius/surgeon

Figure 8. Architecture of the Hugo® system

Figure 9. Focus on the Hugo® arm with mobile elements handling the instruments and sliding along long arm.
Figure 10. Product innovation and process innovation when dominant design is established
Abernathy, 1978; Suarez, 1993

Figure 11. Placement of the robot into the operating room emphasizing layout issues.
Pr Mordant, personal communication, unpublished.

Figure 12. Architecture of the Vicarious® system.
https://www.vicarioussurgical.com/

Figure 13. Architecture of the Moon® system. The instruments are not specific to the device.
https://www.moonsurgical.com/

Figure 14. Different types of controllers.
https://cmrsurgical.com/versius/surgeon
https://www.aurishealth.com/monarch-platform

Figure 15. Haptic gloves.
https://haptx.com/

Figure 16. Flexibles arms.
https://www.momentissurgical.com/anovo-surgical-system/
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Figure 17. Advantage of the mobile cameras in the Vicarious® system.

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Figure 18. Preoperative 3D reconstruction of the organ and tumor (here, a tumor in the right upper lobe of the lung) and their inclusion on the robotic imaging display (here, the division of the mediastinal artery of the upper lobe of the lung).

Pr PB Pagès, private communication, unpublished.
ANNEXE 2 – Historical perspective

a. Definition.
The definition of surgical robotics is not unanimous because the definition of a robot is not. According to the Collins dictionary, a robot is an automated machine programmed to perform specific mechanical functions in the manner of a human (Collins, 2020). According to an online encyclopedia, a robot is a device that combine mechanistic, electronic and informatic elements in order to perform specific tasks that mimic human actions (Wikipedia, 2022). The word “robot” is therefore associated to a certain degree of automatization that vary greatly according to the underlying technology and the field considered. The classification of Lavallee distinguish active, semi-active, and passive robotic system (Lavallee, 1991). For example, most industrial robots used in the automotive industry are automated to perform a task following a predefined program under human supervision but with no human action. At the other extremity of the spectrum, most domestic robot have long been passive as could be a cooking robot – even if more recent domestic robots are now capable to automatically map and hoover a room with no human action.

b. Task-specific robot
Forty years ago, the field of robotic assistance in surgery has been explored through 2 different ways. The first surgical cases of robotic assistance were with semi-automated task-specific robots. In 1984, a revamped industrial robot, the PUMA 560 robotic system, assisted with a stereotactic brain biopsy under CT guidance (Kwoh, 1988). In the late 1980s, the Imperial College in London developed a robotic system named Probot® to assist in prostate removal through natural orifice (Davies, 1991). Using a computer-generated 3D model of the prostate, the surgeon outlines a specific area for resection. Based on these data, the Probot® calculates the trajectories of excision and the procedure is executed by the robot without any further assistance from the surgeon (Harrys, 1997). In the field of orthopedic surgery, Robodoc® (Integrated Surgical Systems, Sacramento, CA, USA) has been developed to assist surgeons in total hip arthroplasty. Using a high-speed drill in conjunction with patient Computed Tomography (CT) data for accurate guidance, the Robodoc® bores a precise hole in the femoral head that allows the surgeon to optimize the prosthesis size on a patient-specific basis (Paul, 1992). Even if the task of drilling a bone or a prostate can be considered as simple, both devices have some kind of automation to plan and adapt itself to the exact anatomy of the patient (Kalan, 2010).

c. Telesurgery
In parallel to these task-specific devices, larger research efforts were supported by US federal agencies in the field of telesurgery. In the mid 1980s, the National Aeronautics and Space Administration (NASA) was interested in the development of head-mounted display for displaying the massive amounts of data being returned from planetary explorations (Satava, 2002). Specific gloves were developed to allow interaction with the three-dimensional virtual scenes. When this technology allowed to show 3D images
and to interact with it remotely, researchers sought to explore the surgical field. A collaboration with the biomechanics section of Stanford Research Institute and the clinical input from a plastic surgeon fostered the concept of distant surgery or telesurgery, with the ultimate goal to set an extremely dexterous telemanipulator that greatly enhances human precision to perform vessels and nerve sutures for hand surgery (Kalan, 2010). The project then benefited from additional funding and competencies from the Defense Advanced Research Projects Agency (DARPA). During the 1990s, the goal of the DARPA was to develop distant surgery in order to offer surgical care to the wounded soldiers on the battlefield. From a technological standpoint, the solution was the use of 3D glasses and intuitive remote control by a surgeon placed in the Mobile Advanced Surgical Hospital (MASH) up to 5 kilometers away from the battlefield, communicating by microwaves with a robotic arm that could be placed close to the wounded soldier at the rear station of a military vehicle (Satava, 2002). However, the typical battlefield rapidly moved from open countryside to urban area, and despite successful experimental procedures with a surgeon operating on an animal or a patient anaesthetized up to 6000 km away, the idea of distant surgery did not gain enough interest to foster wide adoption (Marescaux, 2001).

d. General surgical robot

Interestingly, the concomitant development of VAS and the first case report of laparoscopic surgery provided a natural opening for the application of robotic surgery and the development of RAS. In 1994, the first commercially available robot was the voice-directed camera system AESOP® (Automated Endoscopic System for Optimal Positioning, Computer Motion Inc, Goleta, CA). This system has then been enriched with 2 robotic arms and a mechanical remote-control in the ZEUS® system (Computer Motion Inc, Goleta, CA). In 1999, Intuitive Surgical developed the Da Vinci® system (Intuitive Surgical, Sunnyvale, CA), with one surgeon console, one patient cart, and 3 robotic arms including a 3D imaging system (Kalan, 2010). The first clinical application was cardiac surgery to benefit from the minimally invasive access, vision enhancement and tremor regulation offered by the system (Loulmet, 1999). These demonstrative cases might also have been very useful to convince investors, raise funds and industrialize the production process of the system. The Da Vinci® system has been available and regulatory approved in Europe in 1999, and in the US in 2000. It has initially been cleared for general laparoscopic surgery, and has subsequently been authorized for use in cardiac, thoracic, urological and gynecological procedures. In 2003, Intuitive Surgical bought out Computer Motion, thus ending ZEUS® and AESOP® (Kalan, 2010). For 20 years, Da Vinci® has been the only general surgical robot commercially available (Pugin, 2011).
ANNEXE 3 – Future perspectives

*Small-scale robotics.* Microelectromechanical systems (MEMS) are in the range of millimeter to micrometer. Such systems would be visible as very tiny robots that could be directly controlled by a surgeon. However, as the technology is scaled down in size, it also is scaled down in power or the force that can be generated, making it extremely difficult to actually conduct work at this scale. Although there are a number of MEMS robots, none are actually performing any significant work, let alone any activity resembling a surgical procedure (Satava, 2002). An interesting field of investigation is the development of magnetic miniature soft-bodied robots that might allow non-invasive access to restricted spaces, thus providing ideal solutions for minimally invasive surgery. Such magnetically actuated miniature soft robots can be based on elastomer (silicon) or liquid metal (ferrofluid), with important limitations regarding ability to reconfigure for elastomer-based robots, and ability to adapt for fluid-based robots. New materials included non-Newtonian fluid-based magnetically actuated slime robots, with both the adaptability of elastomer-based robots and the reconfigurations of fluid-based robots (Sun, 2022). In a recent study published in Advanced functional materials, researchers used neodymium, a strongly magnetic metal, covered by a silicon coating, to develop magnetic slime robot controlled by magnetic fields. These robots can be combined into modular robot. As it can progress on a variety of surfaces and even underwater, such robots could be of interest for the digestive tract (Sun, 2022; Hong, 2022), however, the development of magnetic slime is still very early phase.