Chapter 1.1

General introduction
Robotic telemanipulation systems were introduced during the last decade of the 20th century. They were developed to support surgeons during endoscopic procedures, in which visualisation and manipulation are reduced as compared to traditional “open” surgery.

In June 2000, a da Vinci robotic telemanipulation system was acquired in a cooperation between the department of surgery of the University Medical Centre Utrecht and the Heart-Lung Centre Utrecht. At the same time, a second da Vinci system was installed for experimental use at the Central Laboratory Animal Institute.

On the 26th of June 2000, the first robot-assisted laparoscopic procedure in the Netherlands was performed in our hospital, followed by well over a hundred interventions on the digestive tract in the following years. In the animal laboratory, technically more challenging procedures were assessed.

This thesis describes the Utrecht experience in experimental and clinical applications of robot-assisted surgery. Feasibility of various robot-assisted procedures was assessed and in a later phase, experimental studies focussed on the comparison of robot-assisted surgery to standard “open” and laparoscopic techniques, aiming at assessing the benefits, challenges and potential pitfalls of using this new technology.

The aim of this thesis was to answer the following questions:

1. Is it feasible to perform both basic and more complex endoscopic procedures with the use of robotic assistance?
2. Does robot-assisted surgery offer benefits over standard endoscopic surgery?
3. Is there a role for robot-assisted surgery in day-to-day clinical practice?

The outline of this thesis

In chapter 1.2, a review of robot-assisted surgery is provided at the moment of acquisition of the robot-system in June 2000. This is followed by a description of the da Vinci system in chapter 1.3.

Chapters 2 to 5 focus on the clinical applications of robot-assisted surgery. Chapter 2 demonstrates our early experiences with robot-assisted surgery in a relatively simple procedure, the laparoscopic cholecystectomy. Chapter 3 goes into detail on time consumption during laparoscopic cholecystectomies, comparing robot-assisted and standard laparoscopic procedures. Chapter 4 describes our experience in Heller myotomies. Safety and efficacy of this procedure, both in functional and symptomatic parameters, were assessed. Chapter 5 summarises and discusses our overall clinical experience during the first three years of robot-assisted surgery and discusses our vision on the future directions of robot-assisted surgery.

Chapters 6 to 9 concentrate on our experimental experiences in animal studies. Chapter 6 addresses the safety and efficacy of robot-assisted laparoscopic intestinal anastomoses, compared to standard, hand-sewn, open anastomoses. Chapter 7 compares robot-assisted laparoscopic choledochojejunostomies to identical procedures
performed through a laparotomy. In Chapter 8, the comparison of standard endoscopic versus robot-assisted endoscopic surgery is made while performing ex-vivo intestinal anastomoses. Finally, in chapter 9 robot-assisted endoscopic surgery and standard endoscopic surgery are compared in a pig model for end-to-end interposition grafts of the abdominal aorta.

Chapter 10, to conclude, discusses the content of this thesis in general.
Chapter 1.2

Robot-assisted surgical systems: a new era in laparoscopic surgery
Abstract

The introduction of laparoscopic surgery offers clear advantages to patients; to surgeons, it presents the challenge of learning new remote operating techniques quite different from traditional operating. Telemanipulation, introduced in the late 1990s, was a major advance in overcoming the reduced dexterity introduced by laparoscopic techniques. This paper reviews the development of robotic systems in surgery and their role in the operating room of the future.

The widespread introduction of laparoscopic techniques during the last decade of the 20th century was one of the most prominent changes in modern surgical practice. Many open surgical procedures, such as cholecystectomy, inguinal hernia repair and oesophageal reflux surgery, have been reduced to minimally invasive interventions. This has benefits for the patient in a shorter postoperative stay in hospital, less pain, a better cosmetic result and a faster return to normal activity.

Despite a growth in the range of laparoscopic procedures, surgeons remain hampered by the limitations imposed by remote operating. The recent introduction of computer-aided instruments, such as robotic surgery systems, has the potential to revolutionise endoscopic surgery by allowing surgeons to use their traditional open surgery skills for laparoscopic operations.

Shortcomings of current endoscopic surgery techniques: the base for new developments in surgery support systems

In open procedures, the surgeon has unlimited flexibility in positioning his body, elbow, wrist and fingers; the operative field may be approached from various directions, and the surgeon controls his actions by visual and tactile feedback. During endoscopic surgery, the problem of working with long instruments through fixed entry points and looking at a screen greatly reduces this feedback. The surgeon’s actions are further compromised by limitation of the movement of the instruments to only four degrees of freedom (DoF). The angular displacement of the instruments inside the body following a movement of the surgeon’s hand hereby varies according to the length of the instrument that is introduced into the body. The hand-eye coordination is further reduced by the loss of the eye-hands-target axis, compromising normal oculo-vestibular input 1. Basic surgical manoeuvres like suturing, therefore, demand highly developed technical skills that the surgeon needs to learn.

Looking at a two-dimensional screen, surgeons are handicapped by the loss of the visual perception of depth and, additionally, by the need for a human assistant to hold and move the camera. The latter causes discomfort, because the field of view is no longer under the surgeon’s own control. Orientation errors and unstable camera control may compromise the smoothness of the operation.

Although many abdominal operations can be performed laparoscopically at this moment in time, performance of complex minimally invasive surgery is in the hands of a limited number of experts. Therefore, researchers have started to develop new tools for laparoscopic surgery to minimise the unsatisfactory aspects of the process. The launch of robotic telemanipulation systems heralds this development.
Robotic telemanipulation systems: history and current status

Reduced dexterity and impaired visual control were considered the major burdens of endoscopic surgery and initial attempts in developing robotic support systems aimed at enhancing the surgeons' control of the instruments and of the endoscope. The first applications of robotics in surgery were in the field of camera guidance systems.

In 1994, the American company Computer Motion was the first to obtain FDA approval for the use of the AESOP (Automated Endoscopic System for Optimal Positioning) robot arm in the operating theatre. This camera arm mimics the function of a human arm. It was designed to offer the surgeon direct control over the camera system by means of a foot pedal or voice control. The voice recognition system enables voice activation of the camera following previously recorded voice commands. The AESOP arm provides the surgeon with a steady and flexible view of the operative field, independent of the skills of a human camera assistant ⁴.³

At the same time in Germany, the Tiska endoarm (a passive system) was developed which allowed a stable optic positioning by means of electromagnetic friction. This was controlled by a foot-pedal. The arm could also be used as an instrument retractor ⁴. The point of trocar insertion into the abdominal wall is fixed protecting the patient against excessive forces at that point.

The Fips endoarm is an example of an active camera system where the surgeon moves this camera system either manually by a finger ring joystick, clipped on the handle of an operating instrument, or by voice ⁵.

In 1998, the British firm Armstrong Healthcare launched the Endoassist robotic camera assistant for laparoscopic surgery. It moves the camera in synchrony with the surgeon’s head movements making intuitive control of the visual field possible. The camera only follows when a foot switch is pressed, allowing the surgeon to make head movements freely at all other times ⁶.

Whilst developments in imaging systems clearly progressed, dexterity problems remained a crucial problem. In the early 1990s, the concept of a master-slave telemanipulator was developed. This concept required the surgeon to control a manipulation system from a master console remote from the patient. A computer placed between the surgeon’s hands and the end-effectors of the instruments, uses computing power to support the surgeon’s dexterity. The surgeon moves two master devices made to resemble surgical instruments at the console, and each motion is translated to the robotic arms which scale down the movements at the end of the instruments inside the patient’s body. The robotic slave arm follows all commands of the master arm in a natural way, comparable to manipulation in open surgery.

The original goal of developing these telemanipulators was to enable telesurgery. This would allow surgeons to operate on patients from a remote location thus avoiding hazardous environments, such as a battlefield, or inaccessible places, such as outer space. It would also allow them to perform surgery on patients who carry life-
threatening infections. The US Federal Government supported research in this field at Stanford Research Institute and, in the early 1990s, the first master-slave manipulator for surgery was developed. Only four DoF were available in this instrument and, since it filled almost half the operating theatre, it was not a feasible option. In 1994, the technology was licensed to the company Intuitive Surgical.

In Germany in 1992, the ARTEMIS (Advanced Robotic Telemanipulator for Minimally Invasive Surgery) was made. This was the first system that provided instrument mobility with six DoF. It integrated the Fips Endoarm with a conventional technical telemanipulator, mastered by a joystick. The prototype made it to the experimental phase, but neither commercial production nor clinical application was achieved.

At this moment, two US companies have received European Union clearance for clinical application of their telemanipulation systems for general and cardiac surgery. Intuitive Surgical and Computer Motion received FDA clearance in 2000 for general surgery applications with the da Vinci and Zeus telemanipulation systems. Both systems were initially developed for cardiac applications but are still waiting for complete FDA clearance for these procedures.

The Zeus robotic system (Figure 1) consists of three separate robotic arms attached to the sidebars of the operating table. Two arms hold and manipulate a variety of surgical instruments, and one arm handles the camera. The surgeon steers the surgical instruments through two egg-shaped control devices. The Zeus system has recently been integrated within the Hermes system, which gives the surgeon direct control of

Figure 1
A surgeon manipulating the Zeus system. The surgeon is using two manipulators and his voice in order to control the three arms of the system.
endoscopic add-ons. The camera, insufflator, light-source and other additional instruments are adjusted by voice or by a foot pedal. Three-dimensional (3D) vision is incorporated, but requires the use of goggles with shutter glasses.

The da Vinci robot (Figure 2) consists of a master console, where the surgeon sits, looking at a 3D binocular display of the operative field. A three-armed robot cart is at the operation table and the middle arm carries the two-channel optical system. Two independent video images are transmitted to the binocular where they merge thus providing a true 3D image of the operative field. The camera is controlled by the Navigator system, and enables the surgeon to pick up and move the camera by foot pedal. During the camera movement, the slave instruments stay in position. A second foot pedal freezes the instruments, which allows repositioning of the controllers and forearms to an ergonomically favourable position. The control devices have a configuration similar to regular surgical instruments. The surgeon’s movements are transposed to the tips of tiny instruments, where the Endowrist system provides the surgeon with six DoF inside the patient’s body. Control mimics the natural movements of open surgery.

The intuitive control of movements is improved in the da Vinci system by the integration of both the visual system and manipulators in the master console thus restoring the eye-hand target axis. The system goes into stand-by mode when the surgeon moves away from the 3D binoculars.
The major advantage of these newer master-slave robotic systems is the introduction of extra DoF at the end of the instruments, allowing surgeons to manipulate in a manner similar to that of open surgery.

The Zeus offers five DoF, the da Vinci offers six, both with an intuitive control mechanism. In addition, the unnatural opposite response of the instruments is corrected by the robotic telemanipulation systems. Tremors and trocar resistance are eradicated by the man-machine interface. The digital processing allows the scaling down of the surgeon’s hand movements to a level where micro-vascular procedures are feasible. The ergonomic and reduced fatigue features will be a great advantage.

The first operation reported using a robotic telemanipulation system was a laparoscopic cholecystectomy performed on 3 March 1997 at the St Pierre Hospital in Brussels, Belgium. Others have followed in the last few years, not only in general surgery but also in cardiac surgery, gynaecology and in urology. More than 1000 procedures have now been performed with the da Vinci system and almost the same number with the Zeus (Table 1). Instruments are being installed in hospitals in Europe and the US.

<table>
<thead>
<tr>
<th></th>
<th>da Vinci system</th>
<th>Zeus system</th>
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<tr>
<td>General surgery</td>
<td>2220</td>
<td>100</td>
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<tr>
<td>Vascular/ thoracic surgery</td>
<td>1993</td>
<td>570</td>
</tr>
<tr>
<td>Urology/ gynaecology</td>
<td>1145</td>
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Table 1  Number of robotic procedures performed on Jan 1 2002 (Numbers as provided by Intuitive Surgical and Computer Motion).
Robotic surgery systems: future perspectives

The benefits of robotic telemanipulators in the operating room are apparent, but many challenges remain. Proof of benefit for patients has yet to be determined. One of the major points of criticism is the lack of tactile feedback from the operating instruments. Currently, this is only partly compensated for by the 3D visual feedback.

The time to set up the equipment is acceptable for complicated surgery but still too long for daily practice. Whilst experience improves this, the size of the system compromises the proper positioning of the robot in relation to anaesthetic equipment, X-ray facilities, and space to allow the surgeon close to the patient. Integration of the systems into the design of the operating room by attachment to the ceiling or operating table may help.

Next to the usage in laparoscopic surgery, a potential application of this technology is in surgical skills’ training. Virtual reality training programs can be integrated in the system computers and two consoles can be coupled to allow an experienced surgeon to adjust and correct the movements of the trainee. The tutor is able to take over the instruments and show the resident the way to do things correctly. Surgeons that currently use robotic telemanipulators report a significant learning curve in using the system. A double console teaching set-up could considerably diminish this.

Robotic telemanipulation systems potentially offer great benefits for endoscopic surgeons, while enhancing ergonomics, providing additional DoF, three-dimensional visualisation and possibilities for surgical skills training. Challenges remain in implementing these systems in daily practice. In the upcoming years surgeons will have to prove that these systems will offer patients significant benefits that outweigh the additional efforts and costs that are still embedded in their usage.
References


Chapter 1.3

The da Vinci system
The da Vinci system (Intuitive Surgical, Sunny Vale, Ca, USA) is one of the two robotic surgical systems currently available with CE mark/ and FDA approval for clinical use. In our experiments and clinical practice we used this system. It exists of three components connected by cables: the surgeon console, the surgical arm cart and the vision cart (Figure 1).

*Figure 1*

The surgeon console and robotic cart are connected by cables.
The surgeon console

The surgeon operates while seated at a console (Figure 2) with his eyes faced downwards to see the operative field in one line with his hands. Two manipulators, placed in line with the 3-D display of the surgical field, are shaped like traditional surgical pick-ups (Figure 3). The surgeon’s fingers conduct the manipulators and the motions made are detected by sensors. The motions are translated to the tips of

Figure 2
The console of the da Vinci system.

Figure 3
The console integrates two manipulators, placed in line with the 3-D display of the surgical field.
specially designed robotic instruments, which are being held by robotic arms, placed on the surgical arm cart. The 3D view is composed by two images of the operative field. A double (12-mm) endoscope generates these two images that are transposed through separate vision chains to two monitors inside the console. The surgeon’s left and right eye see slightly different images resulting in perception of a 3D image (Figure 4).

Figure 4
Separate images for the left and right eye are displayed in the console, resulting in a true 3D-image of the operative field.

The console integrates a number of foot-pedals (Figure 5): one is for control of the camera system. Once pressed, the robotic instruments stay in position and a move-

Figure 5
The foot pedals (from left to right) for “clutching”, camera control, future applications and diathermy. The middle pedal is for focus control.
ment of the manipulators is followed by a camera action. Another pedal controls the clutch function. This works similar to the camera pedal and allows the surgeon to manipulate the master controls without moving the robotic instruments or camera. Therefore it allows for repositioning of hand and forearms to an ergonomically favourable position. Other foot pedals control diathermy and focus control. Furthermore two basic control panels are integrated in the console. One allows for selection and calibration of the 3D scope, the second for selection of working distance and scaling factor. This last function enables downscaling of motions (2:1, 3:1 and 5:1, e.g. a 3:1 motion scale will move the instrument for 1 cm for every 3 cm of movement of the manipulator).

The surgical arm cart

Figure 6
The robotic arms stretched over a patient’s head. The surgeon console is visible in the background.

The surgical cart (Figure 6-8) is placed at the operating table in respect to the patient’s anatomy. It carries the three robotic arms. Two of these arms are for instruments and are connected to specially designed robotic trocars (Fig. 9). These trocars are introduced in the patient’s body, with a marked pivot point at the level of the body cavity’s wall. The arms move the instruments according to the degrees of freedom of standard laparoscopy and furthermore they control a cable driven mechanical wrist at the tip of the instruments. This wrist provides the surgeon with two addi-
Figure 7
The three robotic arms: the camera arm in the middle and the two instrument arms at both sides.

Figure 8
Rear view of the robotic cart during Nissen fundoplication. The cart is placed over the patient’s head.
tional degrees of freedom of motion compared to standard laparoscopic instruments (Figure 10). The human tremor is not transposed to the instruments but eradicated by a 6 Hz motion filter inside the console. The remaining, middle arm carries the endoscope. This arm is connected to a standard 12-mm trocar.

Figure 9
Robotic instrument trocar (diameter 8 mm).

Figure 10
The da Vinci instruments provide two additional degrees of freedom at the tip of the instrument.
The Vision Cart

This cart (Figure 11) holds all standard accessories for laparoscopy, including an insufflator, light sources, focus control, synchronisers and camera controls. Most important it holds a monitor for the tablesde surgeon (Figure 12). Therefore it is placed in line with the position of the tablesde surgeon and the target area.

Figure 11
The video cart with (from top to bottom): monitor, insufflator, Sonosurg ultrasonic dissection generator (Olympus, Hamburg, Germany), video recorder, light source (2), camera unit (2), focus control and synchroniser (2).

Figure 12
The tablesde surgeon and assistant looking at the monitor on the video cart.