Affording Action

Implementing Perception-Action coupling for Endoscopy

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ISBN 90-9011715-6

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PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van Rector Magnificus prof.ir. K.F. Wakker,
in het openbaar te verdedigen ten overstaan van een commissie,
door het College voor Promoties aangewezen,
op maandag 15 juni 1998 te 13.30 uur

door

Fred Anton VOORHORST
werktuigbouwkundig ingenieur

geboren te Leiden

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This research was supported by the Technology Foundation (STW) under
grant DIO22-2732

Acknowledgements

This thesis would not exist if it were not for a large number of people, whom I would like to thank. First and foremost, Gerda Smets, my promotor, who taught me the importance of the task, the use of empirical research for testing intuitive solutions, and the elegance of simple implementation. Kees Overbeeke, who always allowed me to disagree, and created time to discuss questions about the meaning of life in general and the ecological approach to visual perception in particular. The best location for these discussions is 30000 foot above the ocean, at four o'clock in the morning over a brandy. Pieter-Jan Stappers, computer genius and Mathematica wizard, for his logical thinking and mathematical support. Tom Djajadiningrat, partner in crime, who remained interested despite continuous opposition, who gave 'Thursday evening' new meaning, and who made time to participate in many design and 3rd-Eye projects. Wouter Pasman, who helped with custom made computer programs, who participated in numerous discussions, always able to suggest another rational solution. Tony Subroto, who spend much time behind machinery, proving each time (to my advantage) that a prototype could neither be to small, nor to difficult to build. Ans van Doorn I would like to thank for her fruitful comments and discussions. Although she joined the group recently, she made a smashing impression with her enthusiasm and sharp thinking, but mostly with her eggs in the cellar and her computer in the kitchen. I also would like to thank Onno, 'Princes of Perception' Caroline, Rob (the electronic engineer with the finishing touch), Arnold, Rudolf, Stephan, Jean-Paul and Fons who created a pleasant and stimulating atmosphere. Carlita either made sure there was enough coffee, or made sure I had the key.

Throughout the project, Henk Stassen provided feedback from my old home front. Kees Grimbergen opened doors to the field of medical technology, and introduced me in the AMC were Wouter Sjoerdsma lifted discussions to a 'religious' level and Dirk Meijer provided the opportunity to test many 'wood and wire' solutions in a practical setting. Everyone at Experimental Surgery were very supportive.

I would like to acknowledge the STW (the Science and Technology Foundation) for making this project possible, and the members of the user-committee for their responses. I also would like to acknowledge Olympus, Surgi-Tech, and from the AMC Wim Schreurs and Joris Jaspers, for their interest and enthusiastic participation in the project.

Finally, I would like to thank my family and friends who encouraged and supported me. Most of all, I thank my wife Tonneke for her continuous and loving support.

Contents

CHAPTER 1

INTRODUCTION

This thesis contains research on the implementation of perception-action coupling for laparoscopy. A laparoscope (Fig. 1.1) is basically a long tube with a built-in lens system and light guides. 'Endoscope' is a more generally used name for such a device. Endoscopes are used to observe places which are small and/or difficult to reach. There are many applications for each of which there is a different type of endoscope with its specific size, diameter, flexibility, length, image quality and so on. In general, endoscopes can be divided into two groups: medical endoscopes and industrial endoscopes. Medical endoscopes are named after their specific application. For example, a laparoscope is used to observe the abdomen area (the laparos). Industrial endoscopes, sometimes called borescopes after the bore through which they enter an engine, are named after their specific feature. For example, a borescope with a viewing angle of 90° is called a side viewing borescope.

This thesis focuses on the implementation of perception-action coupling for rigid endoscopes, mostly in a medical context but some in an industrial context. Medical endoscopes will be called laparoscopes, and industrial endoscopes will be called borescopes.

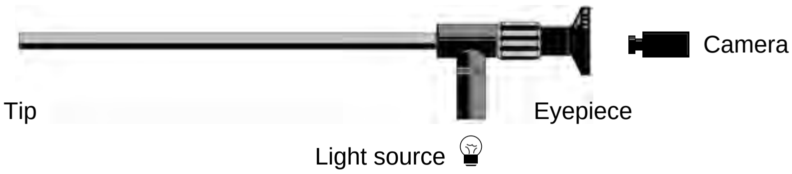

Figure 1.1
A rigid laparoscope, which is used for surgery in the abdominal area.

1.1 The history of endoscopy

At the beginning of the 19th century Bozzini experimented on observing the human anatomy through its natural openings. The main obstruction for doing this was the lack of light inside the body. To solve this Bozzini constructed an apparatus which he called the Lichtleiter. It was the first endoscope and was made of a tapering hollow tube, a candle and a mirror (Fig. 1.2). The candle-light was reflected into the tube by a mirror which had a small opening to make observation possible. The next step in the development was providing for a better view for which candle illumination was clearly insufficient. This problem had two solutions: the total amount of light could be improved or the efficiency of the illumination could be improved.

Firstly, solutions for the total amount of illumination were made. After initial experiments with the Lichtleiter a number of different types of light sources were used. For example, in 1853 a kerosene light source was used and in 1844 the use of a platinum light source was experimented on but this did not work satisfactorily until 1867. In 1880 Edison invented the incandescent lamp of which a miniature version was first implemented for endoscopy in 1883. Nowadays, the amount of light produced by the light sources is sufficient.

Secondly, an increase in the efficiency of illumination was achieved. The first light sources (a candle and a kerosene light source) were located at the point of observation, at the outer end of the endoscope outside the body. Electrical light sources were initially located at the inner end of the endoscope, inside the body. This improved the illumination but had the disadvantage of internal burns. The first attempts to use an optical system instead of a hollow tube were made in 1868. A few years later, in 1899, a glass rod and fused quartz were used to transmit light. By 1914, the combination of the amount of illumination and the efficiency of transmission became good enough to use external illumination.

Figure 1.2
The Lichtleiter [Edmonson, 1991]. This first endoscope and was made of a tapering hollow tube, a candle and a mirror

By the beginning of the 20th century the quality of illumination made it possible to observe large parts of the human anatomy. As light travels in a straight line, endoscopes were straight and rigid. However, the human body is not rigid and because of which only a limited part of the body could be observed with these instruments. Initial solutions to this problem involved minimising injuries by using a flexible outer tube which was inserted before the endoscope was inserted (1908) and using a flexible endoscope which could be straightened after it was inserted (1911).

The limited accessibility of the human body through natural openings led to a new application, namely the use of artificial openings to enter the body. The first experiment to view the abdominal cavity of a dog was performed in 1902 and in 1912 a human pelvis was observed endoscopically for the first time. From this point onward the technical development of endoscopes can be divided into two areas of interest which have developed in parallel: research into entering the body through its natural openings, i.e., flexible endoscopes, and research into entering the body through artificial openings using rigid endoscopes.

Modern flexible endoscopes are based on fibre optics but initially the flexibility of endoscopes was achieved using lenses and prisms. A partly flexible endoscope based on prisms was constructed in 1911. In 1919 the use of a number of short focus lenses to look through a curved tube was patented and in 1932 this system was used to construct a partly flexible endoscope. Flexibility extended possible applications since, after the insertion of the endoscope, it now became possible to explore and look around. The first flexible endoscope which could be actively moved was made in 1941. The idea of exploration after insertion initiated another technical development, namely that of an actively controlled adjustable mirror which was constructed in 1943. By 1949 it was possible to make a flexible endoscope with a diameter smaller than 11 mm. Advances in fibre optics in 1954 and the invention of glass-coated fibres with the required optical properties allowed for the first fibre optic endoscope in 1958. Nowadays, most flexible endoscopes are based on fibre optic techniques.

Research into entering the human body through artificial openings initially had to focus on creating a work-space within the body. In 1910 this was done using filtered room air but by 1926 CO_2-gas was commonly used. The advantages of CO_2-gas over filtered air room were its non-explosiveness and its fast absorption by the body. In 1920 the pyramid trocar point was invented which allowed for precise and clean openings. The rubber gasket was invented in 1924, allowing the retraction and insertion or re-insertion of instruments without releasing gas. In 1944 a method was applied for measuring and monitoring abdominal pressure. Endoscopic operations in the abdomen area (laparoscopy) remained infrequent until the invention of the charged couple device (CCD) video camera in 1986, which made it possible for the surgeon to operate without having to look directly into the laparoscope. Instead, the surgeon could look at a TV screen. Nowadays, laparoscopic removal of the gall bladder and surgical interventions such as hernia repair are common practice in most hospitals.

There are two ways of implementing the CCD camera. It either can be mounted on the eyepiece (Fig. 1.1), or it can be integrated within the endoscope. Which of these possibilities is preferred depends on the resolution required of the image obtained. For flexible endoscopes an integrated CCD camera at the tip is preferred because of its high resolution compared to fibre optics. Until now, a CCD camera mounted on the eyepiece of the laparoscope has been preferred for laparoscopy. A CCD camera on the eyepiece can be larger than one integrated within the laparoscope, and therefore provides an image with a higher resolution. However, it is likely that when CCD technology improves further it will be possible to obtain an image with comparable resolution using a laparoscope with an integrated CCD camera of which the diameter will be small compared to a conventional laparoscope.

For more information about the technical development of endoscopic devices see [Paraskeva *et al.* 1994, Walk 1966, Edmonson 1991, Haubrich 1987, Marlow 1976].

The history of the development of endoscopic devices demonstrates the close relation between development and practical applicability: the interaction between researchers and users. Researchers on the one hand develop the best possible solution for a problem indicated by the user, and users on the other hand apply the developed solution in the best possible way and by doing so explore its limitations. These are reached when there is a difference between what is possible and what appears to be possible. The limitations of current laparoscopic surgery may be identified by defining what appears to be possible, i.e. how laparoscopy ideally should be.

Laparoscopy can be regarded a telepresence task since the surgeon is present at the location where the task is performed only through the medium of the laparoscope and the instruments, and not physically. Telepresence means that enough information about the task environment and the teleoperator (the device which allows the user to perform a task in the task environment) is displayed in a sufficiently natural way for the operator to feel as if he is physically present at the remote site [Stassen *et al.* 1995, Sheridan 1992]. Given this definition, it is obvious that laparoscopy, in its current state, is not yet what it might be. The information about the task environment is limited because haptic[1] and visual information are limited. The information about the teleoperator (instruments and laparoscope) is limited because instruments for manipulation have poor mechanical properties [Sjoerdsma *et al.* 1998, Herder *et al.* 1998] in addition to which the laparoscope is commonly operated by an assistant rather than the actual ‘user’.

Reduced haptic and visual information can be restored in two ways. First, the ability to manipulate can be improved. The instruments used during laparoscopy do not, in general, match the perceptual-motor system of the surgeon, so that his actions are restricted. The instruments can be made more suitable for the actions the surgeon has to perform, for example, by increasing their degrees of freedom and simplifying their handling [e.g., Herder *et al.* 1997 suggest an alternative for commonly used laparoscopic instruments]. Second, the visual information can be improved to suit a spatial manipulation task. Commonly used laparoscopes provide for only limited spatial information. The performance of a spatial manipulation requires information about the lay-out of the work-space in question. This thesis will focus on improving the visual information provided during laparoscopy.

1.2 Depth perception

Depth perception, or more precisely the perception of the spatial layout, is often thought to rely exclusively on binocular disparity: the fact that we perceive the world through two eyes, one perceiving the world more from the right, the other perceiving the world more from the left. Wheatstone [1838] was the first to adequately describe stereopsis based on disparity [Wade, 1987]. This gave the answer to a long standing question: why even the most accurate paintings could be distinguished from the real objects they depicted. The influence of looking with two eyes had been described earlier. For example, Euclid (300 B.C.) describes the effect of observing a sphere with two eyes on the part of the sphere that is perceived [Burton, 1945]. The effect of viewing a picture with two eyes had been described by Leonardo da Vinci, who described the phenomenon that each eye perceives a different part of the background of the object, which is never the case in picture perception. He argued that by looking with two eyes a real object is perceived to be partly transparent since the left eye perceives part of the background that is behind the object and which the right eye does not perceive and vice versa. He took a sphere to illustrate this, which might be the reason why he did not mention anything about the fact that the object itself is also observed differently by each eye [Wheatstone 1838]. Wheatstone was the first to describe binocular disparity as two eyes both perceiving the object from a different angle, and its relation to depth perception. He described the possibility to depict an object in true relief by using two images and the stereoscope.

The implementation of the principle of binocular disparity for laparoscopy was already patented in 1904 (Fig. 1.3) [Zobel, 1993]. However, not until the quality of the lens system had improved and after the invention of the CCD camera and the so-called shutter glass techniques did the stereoscopic laparoscope became applicable. Currently, there are a vast number of technical

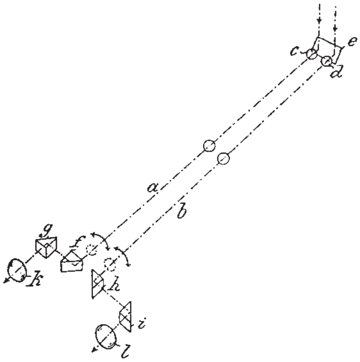

Figure 1.3
Drawing from a patent for a stereoscopic laparoscope of 1904 [Patent no 164966 of the German Patent Office, Source: Zobel, 1993].

implementations which are based on binocular disparity. Tendick *et al.* [1993] have shown that a stereoscopic laparoscope improves endoscopic operation, but that a stereoscopic view alone does not account for the difference between a monocular view and direct viewing. A stereoscopic laparoscope connects to the perceptual system of the surgeon but not to his perceptual-motor system.

Depth perception is caused by more than binocular disparity alone. Perception of the spatial lay-out also relies for example on pictorial depth cues like perspective, shadows, colour, occlusion, texture, an object's position relative to the horizon and an object's relative size. Perspective can be linear or aerial. Linear perspective can be constructed with lines vanishing at one or two points at the horizon (Fig. 1.4). Aerial perspective causes for instance shifting of colour to violet with distance. The larger the distance towards an object, the more its colour will shift to violet. The shadow cast by an object on a surface indicates its location relative both to the surface and to the light source. Occlusion shows the depth order of objects. Texture (Fig. 1.5) is

Figure 1.4
Perspective provides an important depth cue.

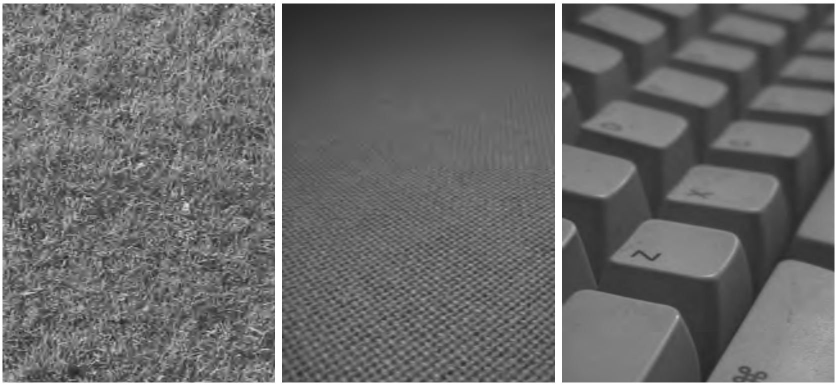

Figure 1.5
Examples of texture gradients [after Gibson 1950].

important for depth perception. Gibson showed that when there is no texture at all, the environment is perceived as being in the mist [Gibson *et al.* 1955b].

These pictorial depth cues depend on, and therefore provide information about, the point of observation. Changing this point will change the relative locations of the objects and shadows, the direction of the texture, the amount of occlusion. Changing the viewpoint by observer movements therefore provides information about the spatial lay-out. The importance of observer movements for depth perception became obvious when railroad trains made rapid locomotion a common experience [Gibson *et al.* 1954]. When looking out of a moving train, objects appear to move. The velocity of these apparent movements changes with the distance towards the moving observer. Near objects flash by while for example the moon appears motionless relative to the observer. These shifts are called parallax shifts (Fig. 1.6).

Within the Design Laboratory at the Faculty of Industrial Design Engineering, Delft University of Technology, the principle of parallax shifts has been implemented to provide an observer, who is watching a monocular camera image on a monitor, with spatial information by linking the motions of the camera to the head movements of the observer (Fig. 1.7). This implementation is called the Delft Virtual Window System or DVWS [Smets *et al.* 1986, Smets *et al.* 1995, Overbeeke *et al.* 1986, the DVWS is described in more detail in Appendix I]. The

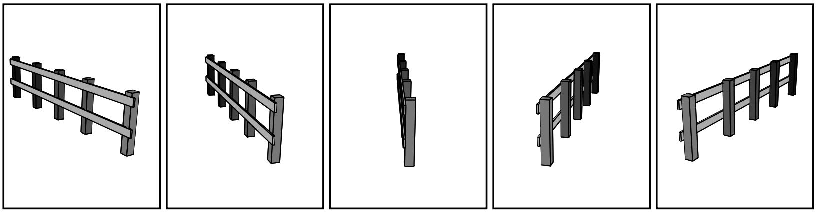

Figure 1.6
An illustration of parallax shifts. Successive views of a row of fence posts for an observer who moves from left to right [After Gibson, 1950].

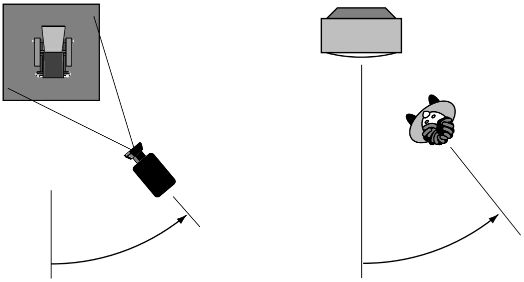

Figure 1.7
The Delft Virtual Window System (DVWS) The motions of a camera relative to a fixation point are linked to the head movements of an observer relative to a monitor.

DVWS allows for depth perception by coupling perception and action and it may therefore be used to improve the surgeon's spatial perception and his performance in spatial observation and manipulation tasks.

1.3 Problem definition

Implementing the DVWS allows the surgeon to obtain spatial information through explorative head movements, and thus relates this spatial information to his own actions. Its suitability for laparoscopy therefore depends on whether surgeons make use of the ability to explore, and whether the information obtained through exploration improves the performance of laparoscopic operation. The main objective of the thesis is:

> *to develop an implementation of the DVWS for laparoscopy which allows the surgeon to explore his working area in order to obtain spatial information in reference to his own actions.*

As the research described aims at implementation it consists of a close interaction between experiments, exploring the feasibility of various implementations from a perceptual point of view, and design, exploring the feasibility of various implementations from a technical point of view.

1.4 Outline of the thesis

The thesis consists of eight chapters which can be grouped into three parts; a theoretical part (Chs 2 and 3) discussing the underlying theory, an experimental part (Chs 4, 5 and 6) discussing six experiments investigating the feasibility of various implementations, and a practical part (Chs 7 and 8) discussing various technical realisations and conclusions with respect to implementation.

The theoretical part (Chs 2 and 3) discusses implementation from an ecological point of view. The basis of this thesis is Gibson's ecological approach to visual perception [1950, 1966, 1979]. This approach starts from the assumption of a coupling between perception and action, which allows a description of the relation between an observer and his environment in terms of task and information. In Chapter 2 the concepts of action, perception, the task to be performed and the affordance of the environment and their relation will be discussed. In Chapter 3, based on the discussion in Chapter 2, an analysis is offered of what information is needed during laparoscopic observation and manipulation tasks. It is concluded that while observation tasks require information about the spatial lay-out, manipulation tasks also require information about how the spatial lay-out relates to the surgeon. Both types of information are provided by the DVWS.

The experimental part (Chs 4, 5 and 6) discusses experiments investigating the feasibility of possible implementations from a perceptual point of view. A total of six experiments are described, which are numbered from 1 to 6 throughout the thesis. In Exp. 1 (Ch. 4) the feasibility of viewpoint parallax for medical application is investigated. The results indicate feasibility for observation tasks, but not for manipulation tasks. Implementation, however, is complex because the mechanism to move the camera has to be built within the endoscope. For this reason the application of a different principle is investigated, namely that of shadow (movement) parallax, which provides similar perceptual information but is less complex to implement. Exps 2, 3 and 4 (Ch. 5) investigate the feasibility of shadow parallax for industrial application. The results indicate feasibility for observation tasks. In Exp. 5 (Ch. 6) both principles are compared for medical application. The results indicate the feasibility of viewpoint parallax for both tasks. For shadow parallax they do not. However, the results suggest the advantage of a combination. In Exp. 6 (Ch. 6) the feasibility of viewpoint parallax is investigated for a more realistic situation, namely the situation in which an assistant holds the laparoscope (contrary to Exps 1 to 5 during which the camera is supported mechanically) while the surgeon controls the movements of the tip. The results indicate that during manipulation tasks the laparoscope should not be held by the assistant, but should preferably be mounted in a mechanical support.

The practical part (Chs 7 and 8) discusses implementation from a technical point of view. This research project has resulted in an implementation of the DVWS (viewpoint parallax) for laparoscopy. In the course of this project, closely related to the experiments, various implementations of viewpoint parallax and shadow parallax for endoscopy were designed; these are discussed in Chapter 7. Technical drawings of these implementations can be found in Appendix II. The final design was developed into a working prototype (Ch. 7), which was tried in a practical setting. Finally, in Chapter 8, conclusions and recommendations for further research and implementation are discussed.

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[1] The haptic system consists of the skin (including attachments and openings), joints (including ligaments) and muscles (including tendons). Its receptive units are mechanoreceptors and possibly thermoreceptors [Gibson 1966, p50].

CHAPTER 2

PERCEPTION-ACTION COUPLING

From theory to practice

2.0 Introduction

This chapter describes the theoretical framework within which the implementation of the DVWS is explored. Two issues are discussed. First, since the DVWS provides for spatial information, it is discussed how the spatial layout is perceived. Within perception theory it is possible to distinguish between two approaches to describing the relation between perceptual information and action possibilities. The classical or indirect approach relates perception to action through an internal representation. The ecological or direct approach links perception to action directly. This allows for a description of perceptual information in relation to action possibilities and thus in relation to the task.

Second, since the implementation of the DVWS is based on a coupling between perception and action, this coupling is discussed in more detail. The discussion of this coupling, however, introduces a number of concepts that are a constant cause for debate, e.g. information, invariant structure, affordances and intention. These concepts will be defined to provide a framework for the task analysis described in Chapter 3. Furthermore, in Chapter 7, these concepts will be used as criteria for the evaluation of proposed implementations.

2.1 Perception of spatiality

There are two main streams discernible in discussions on perception: the classical or indirect perception theory and the ecological or direct perception theory. The indirect theory analyses perception on the basis of an internal representation. It describes how information is perceived. The direct theory focuses on the relation between the user and the environment. It describes what information is perceived. The principles described in this section, although they apply to perception in general, will be discussed in the context of visual perception.

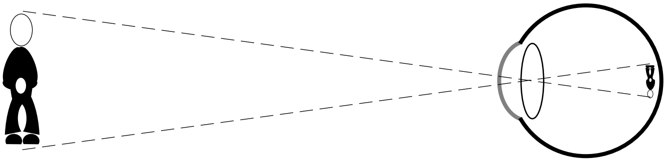


Figure 2.1
The world is projected inversely on the retina.

2.1.1 The indirect approach to perception

The indirect perception theory approaches visual perception from a physiological point of view. The description of the human visual perceptual system starts by describing the eye. It is assumed that opaque objects reflect light in all directions from every point on their illuminated surfaces. At the beginning of the 17th century Johannes Kepler proposed that the retina is illuminated distinctly point by point from individual points of objects [Lombardo, 1987]. These individual points of light together would project an image on the retina. This projection was shown in an experiment with a bull's eye of which the outer back surface had been removed and replaced with a paper. The paper showed a tiny inverted image (Fig. 2.1). The point to point relationship between the world and the mosaic projection of the world on the retina is the basis for the indirect perception theory.

If perception is based on a projection on the retina, which has less information than the spatial world, where does the perception of spatiality come from? The ancient Greeks' belief that physical stimulation was the basis of what could be seen led Kepler to the conclusion that as there was no stimulation defining the third dimension a mental step was required to go from visual sensations to an awareness of spatiality [Lombardo, 1987]. The spatial layout was computed on the basis of the projections on the retina. Kepler's "Telemetric Triangle Hypotheses" and his "Angle of Convergence Hypotheses" (Fig. 2.2) explain how the distance towards an object can be computed from a combination of the distance between the two eyes and the amount of convergence of the eyes. For example, from the distance between

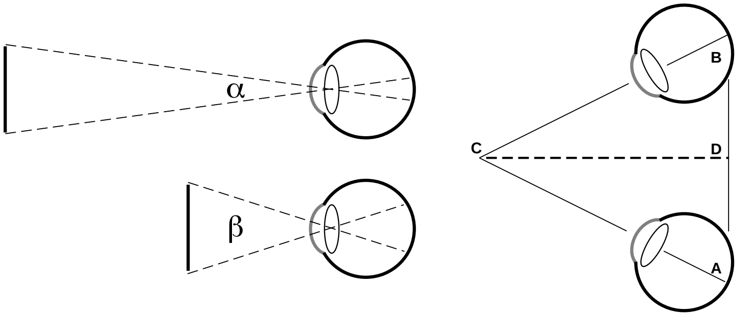


Figure 2.2
Kepler's "Telemetric Triangle Hypotheses" (left) and his "Angle of Convergence Hypotheses" (right) [after Lomardo 1987].

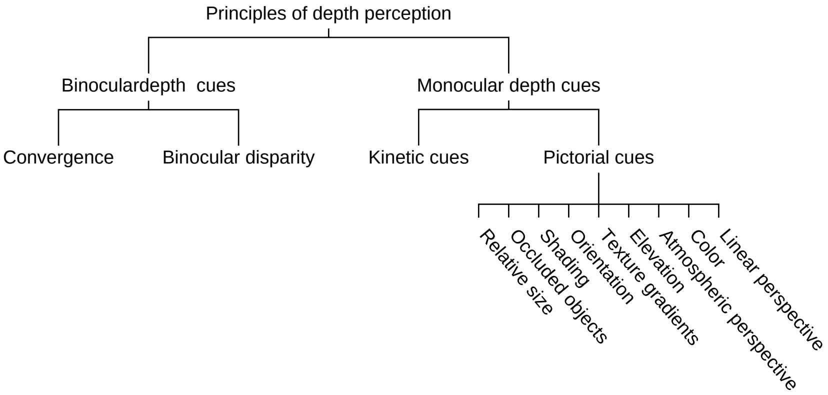


Figure 2.3
An overview of depth cues. For an extended description of depth cues see Overbeeke et al. [1988].

the eyes (AB in Fig 2.2), and the amount of convergence (angle ACB), the length DC can be calculated. Besides converging eyes, pictorial depth cues like perspective, shading, colour, occlusion, texture, the object's position relative to the horizon and the relative size of objects all also provide spatial information. Fig. 2.3 gives an overview of the sources for perception of spatial information [Lombardo, 1987].

To arrive at a percept of the world from the mosaic projection on the retina, the most commonly accepted indirect approach distinguishes three stages. Firstly, the light falls on the retina and gives rise to basic sensations. Secondly, the basic sensations are sent to the visual cortex for feature discrimination like lines, edges and contrast. Here, the image is analysed for structures which together form distinguishable objects. Thirdly, the neural impulses from the visual-cortex are sent to the cerebral-cortex where, in a massively parallel fashion, higher order processing takes place, including cognition and thought to form a percept of the world. Here, the objects which were distinguished by the visual cortex are recognised, using memory and an internal representation1 of the world. Because this internal representation also includes functions, by recognising an object its function is automatically known. For example, from recognising an object as a chair the internal representation of the environment tells you that this chair is a place to sit.

2.1.2 The direct approach to perception

At the end of the 19th century the point to point relationship between the world and the projection of the world on the retina had led to a description of perception in which points or patches on the retina are used for units of experience. Any scene or event was simply the sum of experiences of each point or patch into which the scene can be divided. A major reason why such a description cannot be completely suitable is that the individual points do not describe global properties of the scene that go beyond the properties of the individual points or patches like shading, colour and perspective [Hochberg 1974].

In contrast to visual sensation from local sensory experiences, the Gestaltists assume that perception is based on the entire proximal stimulation[2]. They do not believe that the appearance of a perceived object or scene is the sum of the appearances that would be experienced if each patch into which the scene can be divided were viewed separately [Hochberg 1974]. Instead, appearance depends on the entire pattern of stimulation produced by that object. The entire pattern of stimulation is assumed to be more than the sum of the individual points. The main difference from classical approaches is that the Gestalt explanation of perceptual organisation focuses on relationships and global structures.

The ecological approach to visual perception or the direct perception theory, as formulated by Gibson [1979], does not look at the structure of the stimulation of the retina. Instead, it looks at what is stimulating the retina, name-

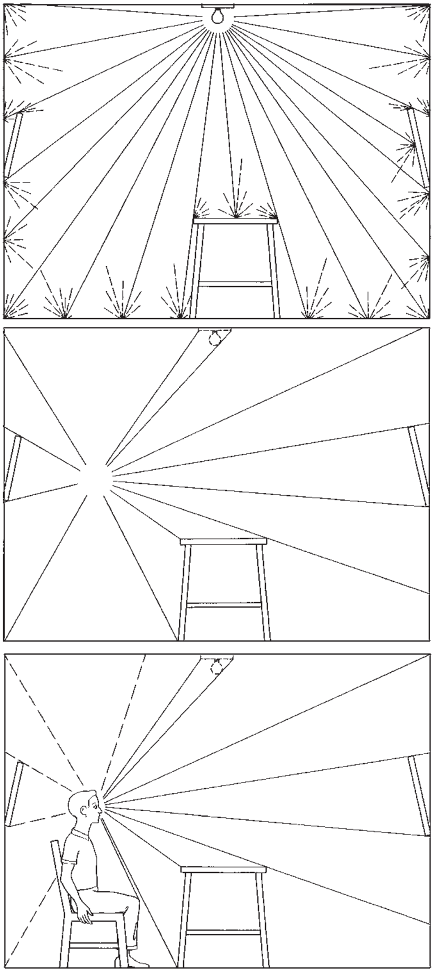
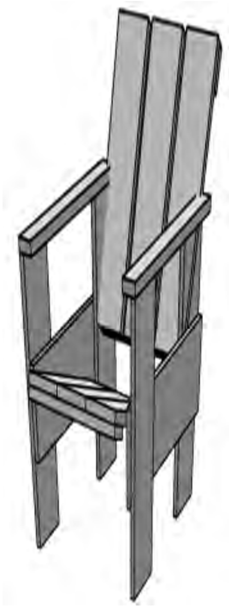


Figure 2.5
From reflecting light to optic array [Gibson 1966]. Light reflects from surfaces (top). This reflecting light is structured, i.e., caused to have boarders within it, by e.g. the reflectance of substances. The middle figure shows the main boarders of this optic array. The bottom figure shows the effective array at a stationary convergence point.
[reprinted with permission of the publischer].



ly light, which itself has structure. That light can have structure follows from how it is described. Light can be described relative to its starting point or relative to its point of arrival. When described relative to its starting point it is called radiant light. Radiant light, because it originates from one point, is the same in all directions and therefore has no structure. When light is described relative to its point of arrival, it is called ambient light. Ambient light, since it arrives from different starting points, differs in all directions and therefore has structure. Ambient light has structure, radiant light does not.

Since the structure of the light uniquely depends on the structure of the environment, the proximal stimulation does not have to be analysed and interpreted to perceive the environment. Instead, the information about the environment can be picked up directly from the optic array. For example, a blind man walking in the street perceives the environment by means of a stick. The modulations of the stick stimulate the sense of his hand but the blind man never perceives a modulating stick. Instead, the structure of the modulations is information and shows the walkability of the floor. The same holds for visual perception: the structure of the light is uniquely related to the structure of the environment.

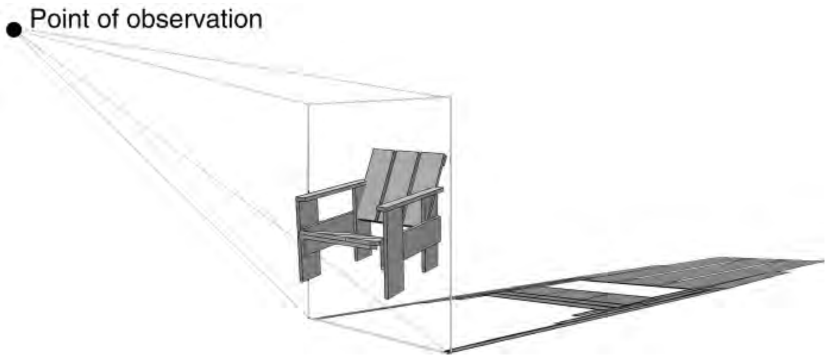


Figure 2.6
This figure shows how an anamorphic picture specifies the viewpoint of the observer. An anamorphic picture is shown on the top-right of this page. To view this picture hold the bottom right of this page close to your eye.

2.1.2.1 The optic array

Structured ambient light is called an optic array (Fig 2.5). The optic array differs for each point of observation (i.e. light arriving at these points) since for each point of observation the environment is uniquely structured. The optic array thus specifies these points of observation relative to the environment and, vice versa, the optic array specifies the environment relative to the point of

Place your eye about here

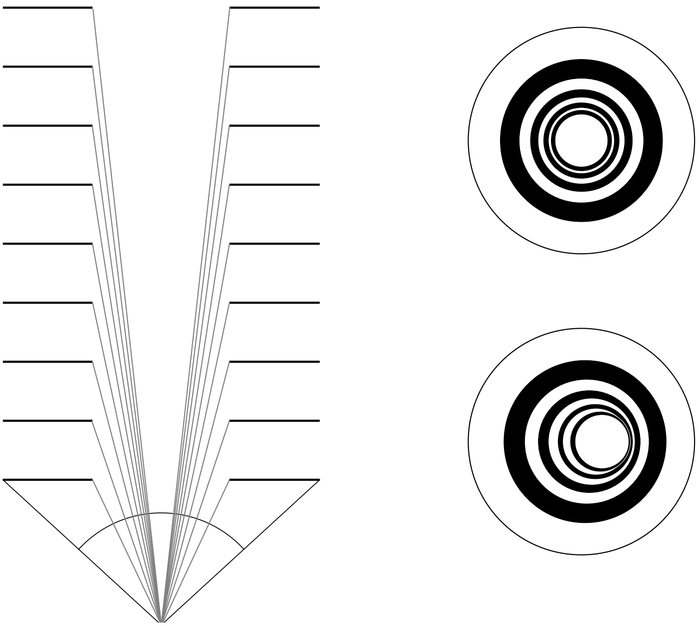


Figure 2.7
Longitude section of an optical tunnel. Nine elements are shown as projected to a single centred eye (left). Perspective cross sections of the optical tunnel (right) [after Gibson 1955a].

observation. This is illustrated by the anamorphic picture3 shown in Fig. 2.6, which can be viewed so that it depicts an undistorted image of a chair, but also so that it depicts a distorted image. The anamorphic picture thus specifies the point of observation relative to the displayed spatial structure. However, within certain limits the perceptual system is robust [e.g. Reinhardt-Rutland 1993], and therefore it will not be noticed that the viewpoint differs from the point of observation of a normal image. For example, a picture of a rectangle shows a rectangle when the viewpoint differs from the point of observation.

Changing the optic array changes the perception of the environment. Gibson [1955a] experimented with a device that presented light rays of which the cross section was a set of concentric rings of alternating high and low density ("white" and "black", Fig. 2.7), producing an optical stimulation for the perception of a solid surface in three dimensions. When the differences in the luminous intensity within the stimulus array approach zero, the surface-like qualities of the percept tend to vanish. Observers had no perception of the environment other than fog or mist [Gibson 1955a].

2.1.2.2 Optic flow

Optic flow is the change in optic array caused by observer movements4. Since the optic array specifies the environment at a point of observation, optic flow specifies the environment relative to a moving point of observation. Rogers *et al.* [1979] used random-dot patterns to investigate the contribution of parallax

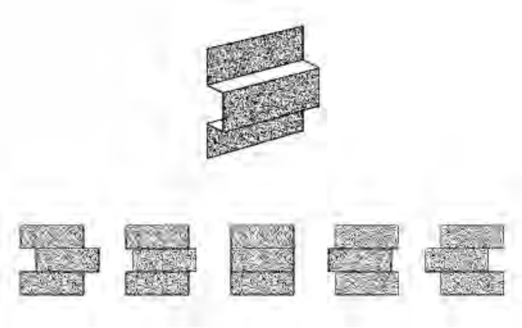


Figure 2.8
Example of stimuli used by Rogers et al. [1979]. Shown are the three-dimensional surface of the stimuli used (top) and the relative displacements of random dots when the observer moves from left to right (bottom) [after Rogers et al. 1979].

shifts to spatial perception. The random-dot patterns are transformed by each movement of the observer and the observer's movements therefore specify a spatial structure which is not specified for a static observer. In other words, the optic flow specifies a spatial structure which is not specified by the optic array. Fig. 2.8 schematically shows a stimulus. In the actual display the random dots always completely filled the screen, while the edges, which are made visible in Fig. 2.8 to demonstrate the principle, were not visible. Fig. 2.8-top shows the three-dimensional surface and Fig. 2.8-bottom shows how the surface is specified by observer movements: it shows the relative displacements of random dots when the observer moves from left to right. Rogers *et al.* [1979] demonstrated the importance of optic flow for obtaining spatial information. The random-dot images used are very abstract representations of normal images. With normal images spatial information is not obtained from movement alone because they always depict static depth cues like shade, perspective or occlusion. However, adding parallax shifts to these depth cues, especially when the parallax shifts are linked to the head movements of the observer, makes spatial perception more compelling.

In short, there are two different approaches which describe perception: the indirect approach and the direct approach. The indirect approach is a psychological-physical approach. It starts from a physiological description of the eye and perception of spatiality is then explained on the basis of binocular disparity and an internal representation. The direct approach, however, is a functional approach. It links perception of the environment directly to actions of the observer within that environment. For implementation, the later is the most appropriate choice since it, as will be discussed in the next section, allows for a description of the task to be performed in relation to the actions possible within the environment and the action possibilities of the observer.

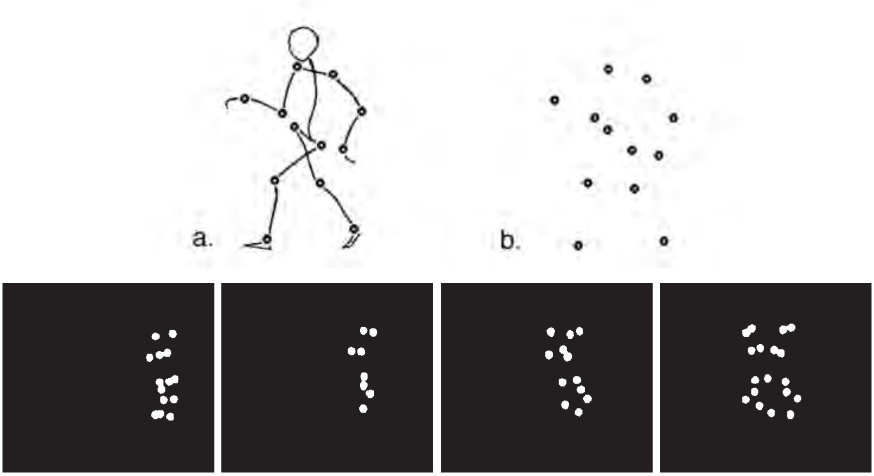


Figure 2.9
The locations of the lights on a person (top-left), and the lights without showing the underlying structure of the person (top-right) [Micheals et al. 1981]. The bottom row shows a sequence of four frames out a movie of two dancers [Johansson 1975].

2.2 Perception of action possibilities

Gibson defines structure as that which is invariant in spite of change [1979, p.73]. In general, a structure reveals itself when its constituent elements behave systematically. For example, Johansson [1975] put 12 lights at various locations of the body of two dancers: at the shoulders, elbows, hips, knees and ankles. The dancers were filmed so that only the lights were visible. Fig. 2.9 shows a sequence of four frames out of this film. While the static pictures appear to show randomly displayed dots, naive subjects who are shown the film can tell in a fraction of a second that they are seeing the movement of two people. Because the dots behave systematically, they reveal the underlying structure (i.e. two people dancing).

The same may hold for the pick-up of structures from the optic array in general. The optic array changes under observer actions in some aspects, while remaining unchanged in other aspects. The way in which the optic array remains invariant therefore specifies this action. For example, invariants of the optic array during observer movements specify these movements. The invariant, if it specifies an action possibility, shows how the environment is meaningful to the observer. Gibson concluded that meaning is not added to a retinal projection by higher order cognitive processes, but that it is perceived directly.

A nice example which illustrates that it is possible to detect higher order information directly, rather than through computation of lower order information, is the polar planimeter (Fig. 2.10) [Runeson, 1977]. The area of a rectangle (higher order information) can be measured by measuring the lengths of its sides (lower order information). The planimeter can measure the area directly, while it cannot measure length. Thus, it can measure the higher order information “area” directly without first having to measure the lower order information “length”.

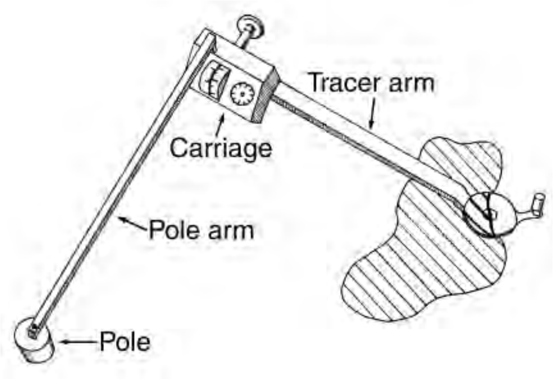


Figure 2.10
A polar planimeter, Lasico, Model 702 [Runeson, 1977]. With it an area can be measured by placing the pole at an arbitrary location and tracing the free arm around the perimeter of the figure. While the planimeter can measure area, it cannot measure length .
[reprinted with permission of the manufacturer].

The idea that information can be picked up directly has met much opposition. Noble [1993] suggests that Gibson referred to “use” instead of meaning since meanings are made by humans from the features of environmental properties. Gibson, however, relates meaning to observer actions. Through exploration (action) of the agent, cause-effect relationships are discovered by the observer. If meaning-making is understood as making sense, i.e. generating adequate action, it can be concluded that meaning is perceived in relation to action. Invariants directly specify what the environment affords and the perception of any object or action possibility becomes picking up the invariant specifying this object or action possibility. Ullman [1980] argues that perception can only be regarded as the direct pick-up of information if the relation between stimulus and precept has no meaningful decomposition into more elementary constituents. However, instead of decomposing into smaller elements, direct perception predicts that combinations of elementary constituents, if informative to the observer, directly result into a precept.

2.2.1. Affordances defined

Information that can potentially be picked up from the structured light direct by any observer is called an “affordance” [Gibson 1977, Gibson 1979]. Affordances are what the environment offers the animal, what it provides or furnishes, whether for good or ill. They relate invariants to action possibilities of the observer. For example, the information of a horizontal surface at a specific height may afford seatability to a person whose knee-height corresponds to the surface’s height. For a person whose waist height corresponds to the surface’s height, e.g. when the observer is a child, it may afford climbability. Fodor *et al.* [1981] argue that unless the notion of pick-up and invariant are constrained, it will always be true that there is an invariant property whose pick-up is sufficient for the perception of any object or action possibility. However, pick-up and invariants are constrained, namely, on the one hand, by the actions which are possible by the observer, and, on the other hand, by the physics of the environment. Moreover, the concept of affordance allows for a description of the environment in terms of action possibilities of a observer and it may do so with respect to a particular observer, taking into account this observer's size, form and capabilities [Mace 1977].

Affordances are, as Gibson held a realistic5 view, i.e. that the world exists objectively, independent from the experiences of the observer. Affordances therefore are defined as properties of the environment and thus they are assumed to be independent of the observer. Heft [1988] suggests that affordances cannot be independent of the observer, but that they are relational, i.e. they define the relation between the observer and the environment. Affordances simultaneously imply both the environment and the observer. By relating the environment to the observer's size, form and capabilities, they show how the environment is meaningful to the observer. An aperture is too small or too high or too narrow, in relation to the observer. The meaning of the situation arises from the interaction of the environment's functional possibilities and intentions of the individual [Heft 1988]. An affordance's functional significance, then, is relationally determined, and may be regarded as dimensionless ratios relating properties of the environment to the properties of the observer [Shaw *et al.* 1995]. Such ratios can be discovered empirically. For example, Warren [1984, 1995] investigated whether comfortable step heights are perceptually specified. It was found that for stairs the comfortable flight height is closely related to the subject's leg length and that subjects are able to perceive which steps are comfortable. Warren calls the relation between leg length and riser height an affordance. However, affordances are not only the geometric dimensions of objects and limbs, but also dynamic properties such as object mass, rigidity, surface friction and so on [Warren, 1995]. They are structures of environmental properties which are perceived in relation to the observer's own capabilities. Affordances are (functional) properties of the environment.

2.2.2 Intention defined

The problem with the concept of affordances is that anything that is picked up can be called an affordance, but that not all affordances that are available are picked up. The question then arises how the selection is made between the available affordances.

To explain how the selection is made between the affordances that are available, various concepts have been proposed. Since affordance is a property of the environment, the concept complementing affordance is a property of the observer. The proposed concepts are ability, referring to what the observer is physically capable of doing, effectivity, referring to potential purposive behaviours, and intention, referring to what the observer wants to do [Greeno 1994, Heft 1988, Turvey 1992, Chow 1989, Shaw *et al.* 1982]. Here, intention is preferred because it reflects the invitational nature of affordances. Thus the affordance refers to what the environment offers the observer, and intention refers to what the observer wants to do.

Arguments similar to those Gibson gave against the indirect perception theory apply to the way in which the concept of intention is used. Gibson argued that there is no internal representation necessary to explain perception, i.e. to regulate the process from proximal stimulation to perception of the environment. Intentions and affordances are mostly described as conditional with respect to perception [e.g. Turvey 1992, Greeno 1990]. Thus, similarly to the internal representation, intention has the purpose of regulating perception, i.e. to regulate the pick-up of affordances. Such a description of affordances and intention discards the most interesting aspect of affordance, namely that it not merely shows an action possibility but that it also invites this action possibility. Here it is assumed that affordance may result in either action or perception. Affordance or an intention, then, interact in an ongoing process.

Using the word ‘intention’ as the complement of affordance suggests that the observer is free of obligation. This may be true in daily life, but not for a work environment, or during an experiment. In these situations the observer will have a specific task to perform. Therefore, instead of using intention, i.e. what the observer wants to do, the task, i.e. what the observer has to do, will be used here to complement affordances.

2.2.3 Linking affordance, perception, intention and action

Two sets of concepts are introduced to describe the interaction of an observer with his environment: the first set consists of action and perception and the second set consists of affordance and the task to be performed (intention). Both sets are closely related. Action and perception point to both the task of the observer and the affordance of the environment and, similarly, task and affordance point to both the action and the perception. This is illustrated in Fig. 2.11, which shows the AπA-model (Affordance-Perception-Intention-Action).

Action and perception are shown against a background of black fading into white. This is done to illustrate the two levels at which action and perception can be described: at a physical level (physical specifications) and at

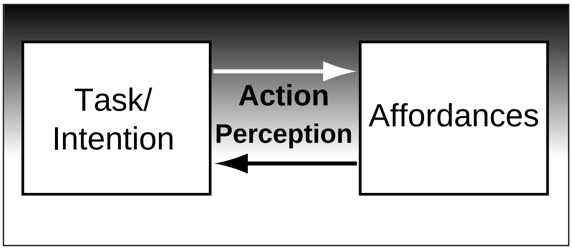


Figure 2.11
The AπA-model relating Affordances, Perception, Intention and Action.

the level of information (informative specifications). At a physical level actions are performed on the environment, or actions are performed to obtain information from or about the environment. At an information level the action itself is perceived or the action results in perception. For example, a surface can be rubbed to perceive its roughness and the action is experienced as a perception. However, the surface can also be rubbed with the purpose of cleaning it of dust, in which case the same action is experienced as an action. Obtaining information can be experienced as a perception or as an action. For example, optic flow can be perceived during locomotion and the visual information is experienced as a perception. Optic flow can also be provided to a stationary observer to make him experience locomotion. Thus, the information obtained is experienced as action.

2.3 Designing for interaction

In the previous section the perception of action possibilities was discussed from a theoretical point of view. This section will discuss it from a practical point of view. It will start with a few examples of self-explanatory devices, after which the concept of affordances is made operational.

Self-explaining is defined as the immediate understanding of something without reasoning or studying. An example which is frequently used to show how a device can be everything but self-explanatory is a remote control for a TV. It has numerous similar buttons on which even more functions are mapped. The relation between the functions and the buttons depends on, for example, which of the multi-layered information screens is currently displayed on the TV. The button itself does not show its function other than with small typography. The layout and the shape of the remote control reflects the engineering underpinning it, e.g. its circuit board. The layers displayed on the TV reflect the flow charts of the circuit board. Flow charts may be self-explanatory for an engineer, for a user they are not [e.g. Djajadiningrat 1998, Chapter 3]. An example of a device which does show how it operates is the Philips kettle designed by Alessi studios (Fig. 2.12). The kettle’s shape clearly shows its ability to be lifted and poured out. The location of the on/off switch and the operation of this control (down is on) are consistent with its usage. Putting down the kettle and turning it on are performed as one routine.

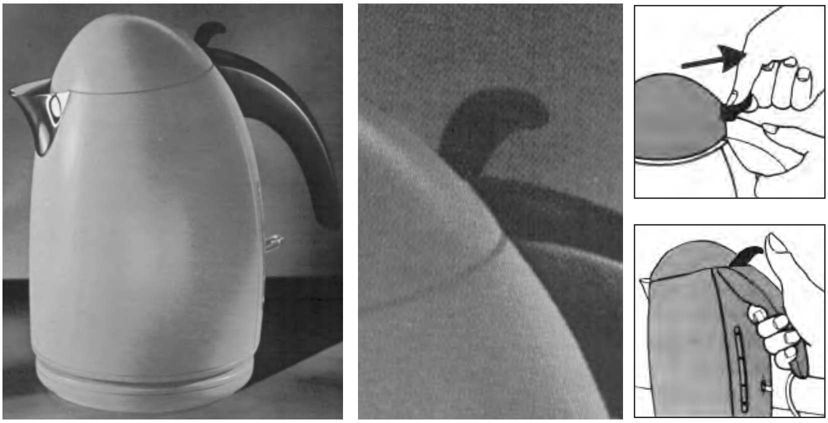


Figure 2.12
Philips kettle designed by Alessi studios. The upper picture on the right shows how the top has to be opened according to the manual, and the lower picture shows how the top invites opening.
[reprinted with permission from the manufacrurer]

The ability of a device to show how it operates is best illustrated with an example of a situation in which the wrong usage is shown. For this, the same Philips kettle can be used. The top of the kettle can be taken off, and to unlock this top there is a lever. The shape of this lever clearly suggests that it should be pushed downwards, as is illustrated with the lower right picture of Fig. 2.12. However, this is not the case. To unlock the top, the lever has to be pulled backwards, as is illustrated in the upper right picture of Fig. 2.12. This conflict between the perceived way of operation and the technical implementation causes users to break the lever off. Recently the lever was redesigned (Fig. 2.13). The new lever has to be squeezed, instead of pulled, which is shown by its shape. Now, its actual operation and the perceived operation agree.

Another example in which the wrong usage is shown is given in Fig. 2.14. This figure shows a dongle, i.e. a hardware protection against illegal copying of computer programs. The computer program checks if the dongle is con-

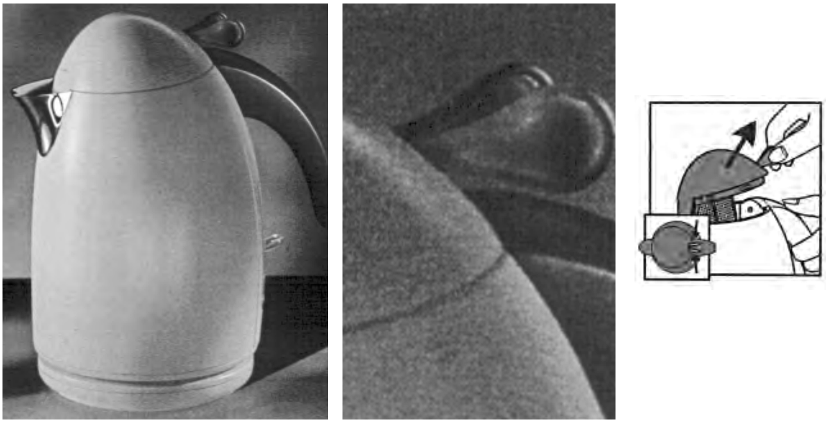


Figure 2.13
The Philips kettle with the redesigned lever. The picture on the right shows the manner in which the new lever has to be operated to open the top.
[reprinted with permission from the manufacturer]

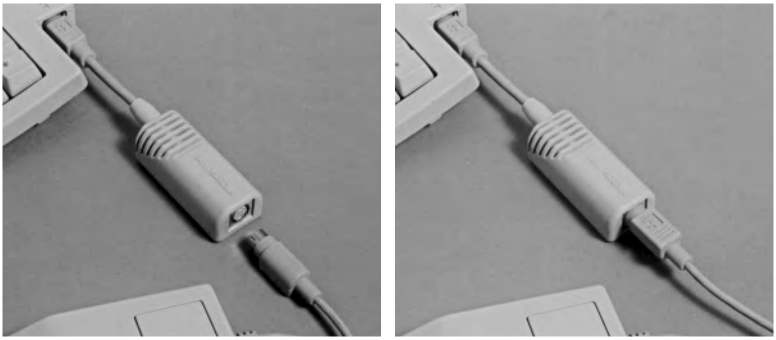


Figure 2.14
The way in which the dongle has to be connected is the opposite of what is suggested by the correspondence in shape between the dongle and the connector. The left image shows the wrong way of mounting the connector, the right image shows the correct way of mounting the connector.

nected to the computer, and will start only when the dongle is detected. Fig. 2.14 also shows the connector, with a shape similar to the shape of the dongle. This similarity in shape suggests that for mounting the connector, it has to be in the same orientation as the dongle but this is not the case. The connector has to be oriented opposite to the orientation of the dongle. The correct way of mounting the connector to the dongle is shown in Fig. 2.14-right.

From the previous examples it can be concluded that there are two types of information a device has to show for it to be self-explanatory. These are: its controlled actions, i.e. what functions of the device are controlled, and its control actions, i.e. how these functions are controlled. For example, the lever of the Philips kettle referred to above must show a) that it can be used to open the top (controlled action) and b) that it has to be pulled backwards (control action).

Both types of information, control and controlled actions, have to be shown in two situations, namely in the situation that the user is a spectator observing the device, and in the situation that the user is an operator using the device. Making this information perceivable for both situations is not as trivial as it seems. However, even for a simple function like opening a door the control and controlled actions are unclear. Norman [1988, 1993] gives a wide variety of examples illustrating how devices do and do not show how they operate. For example, some, mostly glass, doors are not perceived as being a door. If they are perceived as doors, they do not always show from which side they open (on the left or on the right side), or whether they must be pushed or pulled, other than by means of symbols or words. When opening the door, it may not be clear how far the door will open, or whether the door closes automatically or has to be closed. This holds for a simple action like opening a door. When more similar actions are available, or when the number of operations increases, for example with a remote control where the same action (pushing a button) is used to control a wide variety of functions, the perceptibility of operations decreases.

It could be that the examples described above are the result of pure luck, and that it is actually impossible to design, on purpose, a device that shows its control and controlled actions. However, research described by Smets [*et al.* 1994, 1995] indicates the opposite, i.e. that it is possible to visually communicate complex information. In a design course 150 students of Industrial Design Engineering were assigned one of 10 flavours and they were asked to express their specific flavour in a package. Thirty of the resulting 150 packages were chosen by expert designers to use in a matching experiment. A group of design students who did not take this design course and a group of non-designers participated in an experiment during which package and flavour had to be matched. Smets *et al.* [1994, 1995] found that both the design students and the non-design students were able to match a taste and the package designed for that taste. While both groups showed similar underlying patterns, design students differentiated more than subjects without design training. These experiments show that design students are able to convey complex non-obvious information using shape and colour. Complex information can be reflected in, and therefore communicated by, the shape and form of a device. These experiments show that subjects without a background in design are able to pick up this information.

2.4 Discussion and conclusions

In conclusion, there are two approaches to perception, the direct and the indirect. Of these, the direct approach is the most appropriate choice as a framework for implementation [Flach *et al.* 1990, Vincente 1990, Flach *et al.* 1995]. It allows for a description of the task to be performed in relation to affordances, i.e. actions that are possible with the device. Commonly, task analyses are performed at a cognitive level [e.g. Rasmussen 1983]. They relate goal constraints with causal constraints (i.e. what task is to be performed), but they often ignore how (physical action) these are to be performed. Especially the latter is important for implementation. Here, affordances are made operational with control actions, i.e. how the device is operated, and controlled actions, i.e. what is operated with the device. Both have to be considered in implementation. How affordance, perception, intention (task) and action are related is illustrated with AπA-model (Fig. 2.15).

This Chapter has taken a closer look at perception from the point of view of a close relation between perception and action. This approach to perception will be used as a framework for exploring perception-action coupling in laparoscopy and the implementation of the DVWS. What information is needed during laparoscopy is first analysed from a theoretical point of view (Ch. 3), and then empirically investigated with experiments (Chs 4 to 6). The

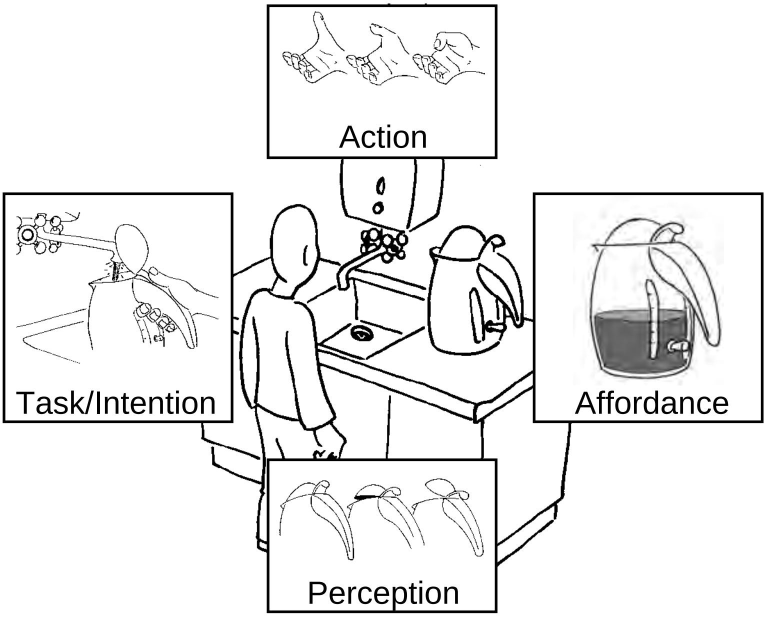


Figure 2.15
The AπA-model (relating Affordance, Perception, Intention and Action) illustrated with the Philips kettle.

exploration of possible technical implementations which provide this information is described in Chapter 7. Note that while experiments and technical realisation are described separately, they were performed in close interaction.

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1 Stassen *et al.* [1990] distinguish between an internal representation and an internal model. The internal representation refers to the subject, and the internal model refers to the researcher's approximation of the subjects internal representation.

2 Proximal stimulation is the stimulation of the sensor (in this case the retina) by the stimulating medium (in this case the light).

3 Note that the optic array, although it is illustrated with pictures, inherently is a spatial structure.

4 Observer movements can either be active, when the observer himself is moving, or they can be passive, when the observer is moved. Note that the latter can also be achieved by moving the environment relative to a stationary observer, who then can have the perception of being moved. For example, At a train station you may perceive the departure of the train on the next platform as your own departure.

5 Realistinc as in the scientific philosophical view that the properties of the environment are not mental constructions.

CHAPTER 3

3D SYSTEMS

A task-based evaluation for laparoscopy

3.0 Introduction

The previous chapter discussed the direct approach to visual perception. Spatial layout was defined as the specification of the environment relative to the point of observation of the observer. A point of observation may or may not be occupied by an observer. When it is occupied, the point of observation relative to the environment coincides with the viewpoint of the observer. The optic array then specifies the viewpoint of the observer relative to the environment. In laparoscopy, the point of observation and the viewpoint do not coincide, as the point of observation is located at the tip of the laparoscope. The surgeon observes the abdomen through a monitor image.

In this chapter various 3D systems proposed in the literature are evaluated for their applicability for laparoscopy. The applicability of these systems depends on what information they provide in relation to the task to be performed. This chapter therefore starts with an analysis of what information is needed.

Figure 3.1
The assistant (on the left) holds the laparoscope as the surgeon (on the right) needs both hands to operate on the patient (on the table). The image obtained with the laparoscope is shown on the monitor (on the left).

3.1 Laparoscopic operation

Fig. 3.1 gives a schematic overview of a laparoscopic operation with the surgeon and the assistant, a monitor and a patient. During laparoscopy the surgeon operates through small "key-holes". Manipulation proceeds by means of special instruments, and observation proceeds by means of a laparoscope (the camera) and a monitor. A laparoscopic instrument is basically an extruded pair of scissors. Commonly used instruments are not well designed with respect to force transmission and ergonomics. For example, Sjoerdsma *et al.* [1997] reported that energy losses of instruments range from 58% to 92%. Herder *et al.* [1997] proposed an instrument based on rolling links [Kuntz, 1995] (Ch. 7), which has an energy loss of only 5%. The ergonomics of instruments was investigated by Crombie *et al.* [1996], who found that 64% of the surgeons participating in their study reported pain and discomfort from the instruments. An alternative interface to common laparoscopic instruments is proposed by Maase [1996, Herder *et al.* 1997]. Apart from reduced force transmission and discomfort, operating laparoscopic instruments also requires practice. Steel *et al.* [1994] describe a number of exercises to learn the basic skills, and to overcome the major hurdle in laparoscopic surgery, namely to develop hand-eye co-ordination using a two-dimensional video image. In some cases it is possible to restore eye-hand coordination by allowing the surgeon to use his hand inside the abdomen. For example, Bannenberg *et al.* [1996] describe a procedure where they make an incision large enough for the surgeon to enter his hand inside the abdomen and attach a plastic sleeve, air-tight, to the skin around the incision. Such a procedure is possible when a large incision is needed, e.g. to remove an organ.

Observation proceeds by means of a laparoscope, which is basically a long tube with a lens system (i.e. a camera) at the outer end (Ch. 1). As the surgeon needs both hands to operate, the laparoscope is held and directed by the assistant. Thus the surgeon has no direct control over his visual information. Commonly used laparoscopes are monocular (provide a 2D image) and therefore provide limited information about the spatial layout. Reduced spatial information hampers manipulation, orientation within the abdomen, perception of the spatial structure and the identification of various tissues. There are a number of technical implementations, 3D systems, that provide information about the spatial layout, that may improve eye-hand co-ordination. Most of these implementations are based on stereoscopy. Stereoscopic laparoscopes are suggested to provide the surgeon with binocular (and thus spatial) information [e.g. Wenzl *et al.* 1994, Pichler *et al.* 1996, Zobel 1993, Mitchell *et al.* 1993].

3.2 Information vs. the task

What spatial information has to be provided depends on the task to be performed. For the surgeon there are two types of task: observation and manipulation tasks. Observation tasks aim at obtaining information about the spatial layout, for example the identification of tissue, orientation within the abdomen and localisation of diseased tissue. Manipulation tasks aim at treating tissue, for example clipping veins and dissecting tissue.

For manipulation tasks binocular information is often suggested. For example, Cole *et al.* [1990] describe an experiment in which they compared binocular and monocular vision. Subjects were asked to manoeuvre a rod through a maze. The maze was constructed to provide minimal monocular spatial information. They concluded that such manipulation tasks require binocular information. Similar results were reported by Spain [1990, Spain *et al.* 1991], who also investigated the advantage of binocular vision over monocular vision when performing the task of placing a peg in a hole. However, binocular vision does not always prove to be an advantage. Kim *et al.* [1987] found equivalent performance for a computer pick and place task when sufficient perspective information is available, for example, cues indicating the position of objects relative to the ground surface. Liu *et al.* [1992] found that for a three-dimensional tracking task in a simulated virtual environment under monocular and binocular vision results in similar performance when monoscopic cues such as occlusion and perspective are present. Brikett *et al.* [1994] reported no advantage of binocular vision over monocular vision for a simple laparoscopic procedure, but did find shorter operation time for binocular vision when performing a complex procedure. Tendick *et al.* [1993] found binocular vision to be an advantage for a pick and place task under laparoscopic conditions, but also found a difference in completion time between monocular direct vision and monocular laparoscopic vision which therefore cannot result solely from the lack of binocular vision. They expected that a binocular laparoscope improves performance, but it will not be as good as binocular direct viewing. However, Hanna *et al.* [1998] compared

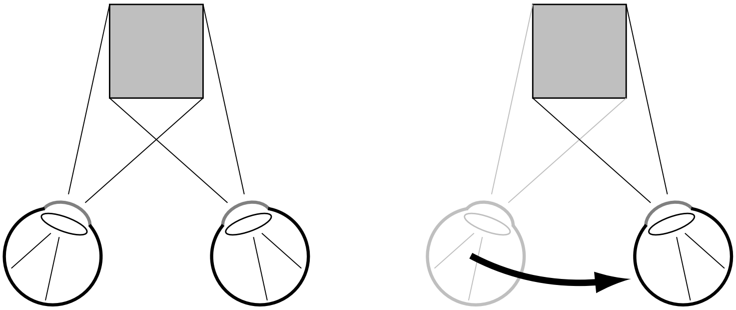

Figure 3.2
Depth perception does not exclusively rely on binocular disparity. A monocular observer, who has the ability to move, is also able to perceive the spatial layout.

monocular and binocular laparoscopic vision in a large clinical study of 60 operations. Contrary to the findings of Tendick *et al.* [1993], they found that binocular did not effect the performance.

While a binocular laparoscope specifies the spatial layout, it does not specify it in relation to the viewpoint of the surgeon. The spatial lay-out is specified in relation to the viewpoint when the surgeon can move. Movement not only allows the perception of the spatial layout without the need for binocular disparity (Fig 3.2), it also specifies the spatial layout relative to the movements, and thus relative to the surgeon. For example, when a vein needs to be clipped, the surgeon has to perceive the direction in which to move the instrument in order to reach the vein. Kim *et al.* [1987] experimentally investigated the influence of the orientation of the laparoscope (the azimuth angle) relative to the working area on the performance of a pick and place task. They found that for angles of 90° or greater, performance of a pick and place task decreased significantly. Holden *et al.* [1998] describe an experiment in which they alter the placement of the camera, the position of the surgeon relative to the workspace, and the positions of the subjects within the work-space. They found, for a pick and place task, that moving the camera relative to the instruments can temporally be very disruptive to co-ordination when either the position of the camera or the position of the surgeon is changed. Wade [1996] differentiates between a geocentric frame of reference, which refers to the world, and an egocentric frame of reference, which refers to the surgeon. He suggests that both frames of reference have to be aligned, for example by using a head mounted display [Geis 1996a], but he fails to identify what specifies a frame of reference. Here, a distinction was made between the viewpoint of the observer and the point of observation within the abdomen. Both are specified visually, namely by the optic array (Ch. 2). The situation inside the abdomen can then be linked to the situation outside the abdomen by specifying the point of observation relative to the viewpoint of the surgeon. There are two ways of doing this:

First, the viewpoint of the observer and the point of observation can be related by moving the instruments relative to the tip of the laparoscope. Assuming that the laparoscope is stationary, a move of the instrument shows the relation between the instrument and the viewpoint of the observer. For example, when the surgeon moves his hand upwards and the tip of the instrument moves sideways, it follows that the laparoscope is tilted.

Second, the viewpoint of the observer and the point of observation can be related by moving the tip of the laparoscope relative to the instruments. Commonly the surgeon has no continuous control over the motions of the laparoscope and thus cannot perceive how the image is tilted and oriented relative to his instruments. Having control provides for spatial information (Ch. 2), for example by moving the laparoscope a specific part of the abdomen can be observed. Moreover, the act of moving makes the spatial information body-scaled, which is important because the surgeon has to manipulate within the abdomen.

In short, during laparoscopy the point of observation and the viewpoint do not coincide. Depending on what task is performed, two specifications are needed. For observation tasks the spatial layout has to be specified relative to the point of observation, i.e. the tip of the laparoscope. For manipulation a specification of the point of observation relative to the viewpoint of the observer is also needed.

3.3 Evaluating 3D systems

The spatial layout is specified either by implementing static depth cues such as shadows, which specify a point of observation within an environment, or by implementing kinetic depth cues such as movement parallax which specify a change in the point of observation through an environment. For observation tasks, the spatial layout can be specified by implementing either position or movement. For manipulation tasks, the spatial layout has to be specified relative to the surgeon. When the surgeon has control over the point of observation, the relation between spatial lay-out and is viewpoint is specified by moving the laparoscope. When the surgeon has no control over the point of observation, this relation is specified by movements with the instruments.

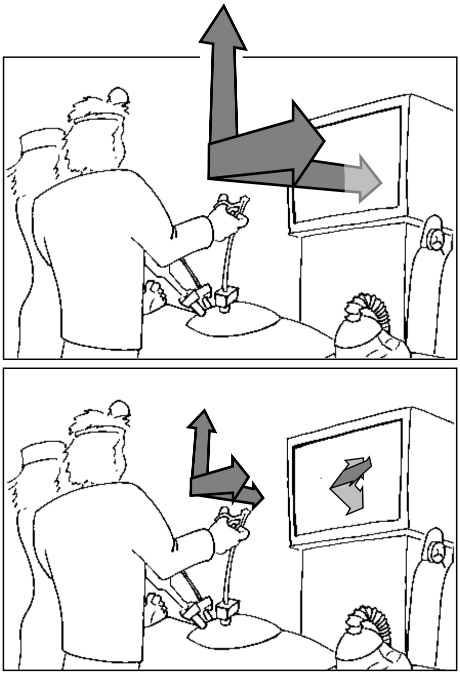

Figure 3.4
When a point of observation is specified then the directions and movements within the abdomen are perceived equal to the directions and movements within the operation room (top). When a change in point of observation is specified, then the directions and movements within the abdomen are perceived relative to directions and movements within the operation room and therefore relative to the surgeon's own movements (bottom).

Control over the point of observation and control over the change in point of observation differ in the effect they have on orientation inside the abdomen, as displayed on the monitor, relative to the surgeon's position outside the abdomen. When the surgeon controls his point of observation, the viewpoint of the surgeon relative to the monitor corresponds to the point of observation relative to the workspace inside the abdomen. The image displayed on the monitor appears to be rigidly connected with the frame of the monitor. As a result, the direction of movements within the workspace is perceived as equal to the direction of movements relative to the monitor (Fig. 3.4-top). For example, a movement of the tip of the instrument towards the left of the workspace is perceived as a movement of the tip towards the left on the monitor. Thus, the location and orientation of the surgeon relative to the monitor and the location and orientation of the laparoscope relative to the working area is important.

When the surgeon has control over the change in point of observation then the image displayed on the monitor is not rigidly connected with the frame of the monitor. Not the position relative to the monitor, but the change in position relative to the monitor corresponds to a change in point of observation relative to the workspace. As a result, the direction of movement within the workspace is related to the point of observation, and thus to the surgeon's own movements (this is illustrated in Fig. 3.4-bottom). For example, a movement towards the left of the workspace is a movement towards the left relative to the point of observation (tip of the laparoscope). This movement does not necessarily correspond to a movement towards the left of the monitor. Now only the location and orientation of the surgeon relative to the working area are important.

Based on this description possible technical implementations can be classified on the information that they specify (a point of observation or a change in point of observation), and whether or not they provide the observer with control (Table 3.1). In the next four sections examples will be given for each of the four possible implementations of Table 3.1.

Table 3.1: *Overview of possible implementations for movement and position, over which the observer either has control or no control.*

	Movement	**Position**
No control	changes in point of observation is independent from changes in viewpoint	point of observation is independent from the viewpoint
Control	changes in point of observation depends on changes in viewpoint	point of observation depends on the viewpoint

3.3.1 A changing point of observation without control

When a moving point of observation is implemented without providing the observer with control, the spatial layout is specified but the observer cannot relate it to his viewpoint. Because the point of observation keeps moving, such technical implementation may not be feasible for manipulation tasks. Hence, during manipulation the direction in which a movement is to be made is perceived relative to the point of observation and when the surgeon does not control the point of observation, the direction in which the movement is to be made is perceived to change with the changing point of observation. Such technical implementation may only be feasible for observation tasks such as visualisation of data obtained with an MRI[1] scanner. MRI scanners produce enormous amounts of data from which a full three-dimensional digital representation of e.g. the human head can be reconstructed. The spatiality of this reconstruction can be made perceivable by rotating it at constant velocity on a screen.

Jones *et al.* [1984, Barham *et al.*, 1990] describe a 3D system, VISIDEP, which is based on a moving point of observation without providing the observer with control, for which an implementation for laparoscopy has been suggested [McLaurin *et al.* 1987]. This system provides spatial information through vertically displaced images which are in sequential alternation. However, as discussed in the previous sections, enhancing the laparoscopic image with a moving point of observation seems only feasible when the surgeon does not manipulate, but when he is only observing. A moving point of observation during manipulation is not practical since it continuously alters the surgeon's frame of reference.

A moving point of observation also occurs when the laparoscope is directed by an assistant creating motions beyond the control of the surgeon. That this situation is unfavourable can be concluded from the vast number of mechanical support systems proposed as alternatives for the laparoscope being controlled by the assistant. A mechanical support system keeps the laparoscope stationary but has to be readjusted whenever the view on the working area changes (Ch. 7). Readjustments can be made easily by the surgeon when a robotic support system is used, for which various technical solutions are being developed. For example, the motions of the robot can be linked, after a pedal is pressed, to the head movements of the surgeon [Finlay *et al.* 1995]. The surgeon can switch between preprogrammed views by pressing a pedal [Gracia *et al.* 1996, Sakier *et al.* 1994]. Other solutions involve voice control [Geis *et al.* 1996-b], or joystick control [Begin *et al.* 1995, Taylor *et al.* 1995] which can either be located within arm's reach or attached to one of the surgeon's instruments.

3.3.2 A changing point of observation with control

When a moving point of observation is implemented and the observer is provided with control, the spatial layout is specified and the observer can relate the point of observation to his viewpoint. Such implementations are feasible for manipulation tasks as well as observation tasks, since they not only specify the spatial layout relative to the point of observation, but also the point of observation relative to the viewpoint of the observer.

An example is the Delft Virtual Window System [DVWS, Smets *et al.* 1995, Smets *et al.* 1987, Overbeeke *et al.* 1987]. The DVWS incorporates a camera which can rotate around a fixation point and whose motions are linked to the head movements of the observer (Fig. 3.5). The link between the camera motions and the head movements allows the observer to explore his working area. An observer exploring his working area, i.e. moving around it and observing it from different angles, creates apparent shifts within his viewing area. These are called movement parallax shifts. Objects behind the fixation point appear to shift together with the observer and objects in front of the fixation point appear to shift opposite to the observer. Shifts similar to movement parallax, can be generated on a monitor screen by rotating the camera around a fixation point. The velocity of these shifts on the monitor depends on the distance towards the fixation point. An observer controlling the camera is able

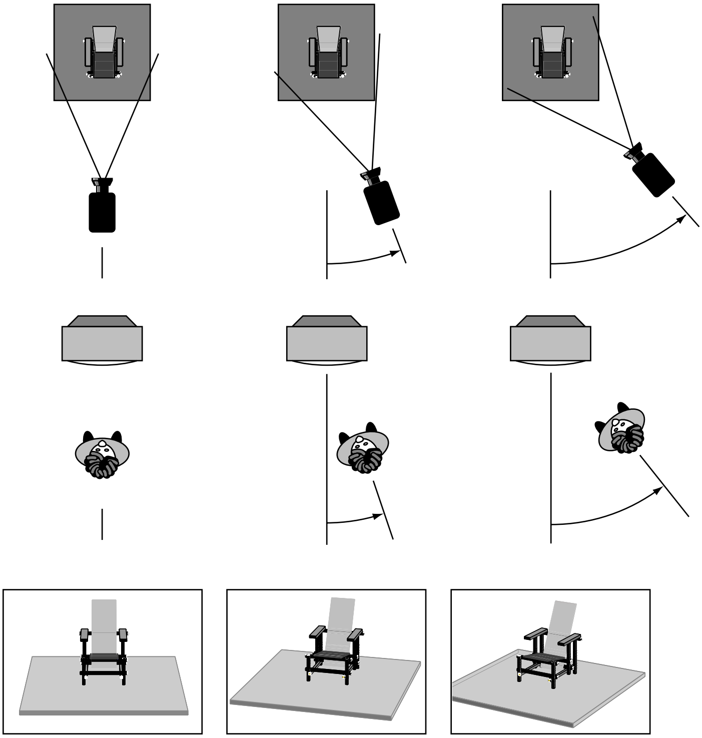

Figure 3.5
The principle of the Delft Virtual Window System (top), and the images displayed on the monitor for different viewpoints (bottom).

to make accurate size and distance estimates. The main difficulty when applying the DVWS to laparoscopy is the design of a mechanism that can create the appropriate camera movements and that also can fit within the laparoscope (Ch. 7).

The DVWS shows similarities with the robotic laparoscopic support controlled by head movements described by Finlay *et al.* [1995]. However, there are two differences. First, the DVWS aims at rotating the laparoscope around a fixation point whereas a laparoscope supported by a robot will rotate the laparoscope around the point where it enters the abdomen. Second, the DVWS aims at continuous control over the motions of the laparoscope whereas robotic support systems, as they are currently implemented, provide for discrete control. For example, a pedal has to be pressed before the surgeon can adjust the orientation of the laparoscope.

3.3.3 A point of observation without control

When a point of observation is specified without providing the observer with control, the spatial layout is specified but the observer cannot relate it to his viewpoint. Such implementations are feasible for observation tasks. Also, when the point of observation (the tip of the laparoscope) remains stationary, such implementations may be feasible for manipulation tasks because then movements with the instruments relate the point of observation to the viewpoint.

Observation by means of a laparoscope and monitor differs in two ways from direct view. First, the monitor imposes flatness cues such as, e.g. dust on the surface of the monitors, the limited amount of pixels a picture is made out of, and reflections on the monitor. A technical implementation which reduces these flatness cues is the so-called reduction screen (Fig. 3.6). A reduction screen is a light absorbing screen with a rectangular opening that is slightly smaller than the size of the monitor screen. Placing this screen in front of the monitor reduces the flatness cues because the image appears to float in air. Another technical implementation that reduces flatness cues is the Suspended

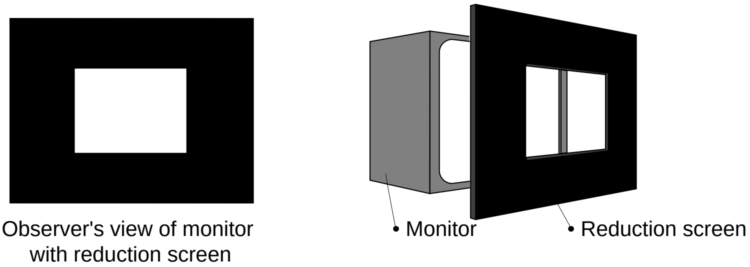
Observer's view of monitor with reduction screen

Figure 3.6
A reduction screen which is placed in front of the monitor to remove flatness cues.

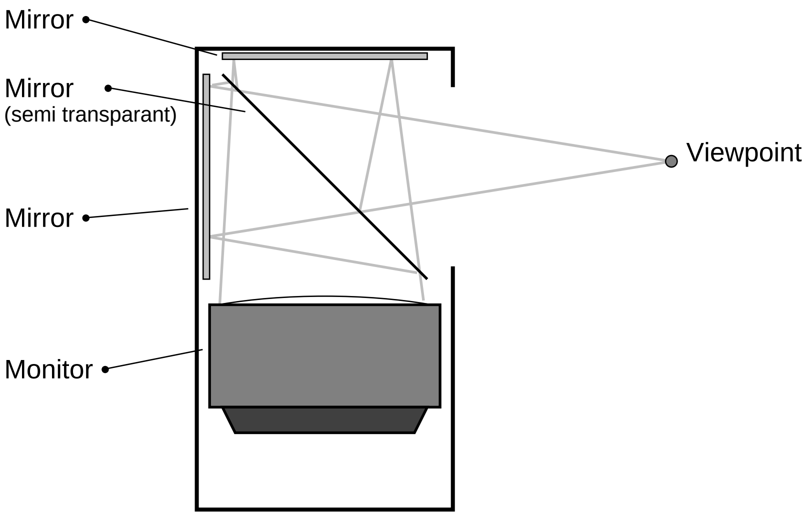

Figure 3.7
The Suspended Image System which reduces flatness cues.

Image System (SIS) described by Cuschieri [1996]. The SIS mirrors the monitor image to appear at a different location (Fig. 3.7), thus separating the image from the monitor on which it is projected. Again, the image appears to float in air.

Second, observation by means of a laparoscope differs from direct view because depth cues are reduced by the system used. For example, the wide viewing angle of the laparoscope's lens (fish-eye) provides a distorted view. Smith *et al.* [1992] propose a computer algorithm to correct for the distortion imposed by the fish-eye lens. The algorithm they describe reduces the distortions imposed by the fish-eye using a simple desktop computer. Also, the contrast of the monitor image is limited. Paz-Partlow *et al.* [1996] found that cameras with digital enhancement are preferred. The contrast enhancement is perceived as sharper edges and increased detail, which helps to identify tissue. Another reduction of depth cues is the integration of the camera and the light source into one instrument. As a result, shadows are less visible and the image is flattened (Ch. 5). Schurr *et al.* [1996] describe a laparoscopic system

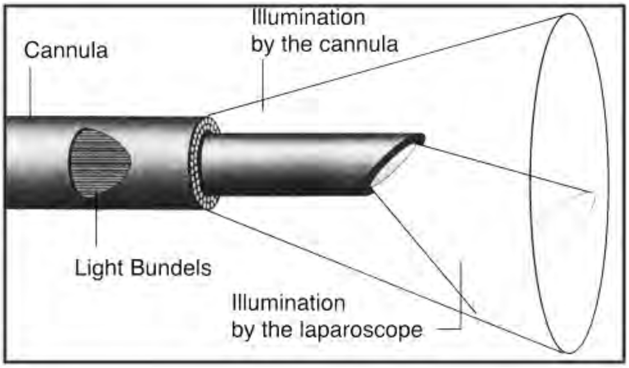

Figure 3.8
Light guides integrated within the trocar to introduce diffuse illumination [Schurr et al. 1996].
[reprinted with permission from the authors]

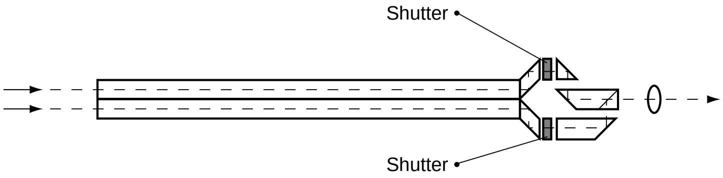

Figure 3.9
Schematic overview of laparoscope proposed by McLaurin et al. [1990].

which introduces diffuse illumination by integrating a light source into the trocar (Fig. 3.8). Yet another reduction of depth cues is the lack of binocular disparity. Under direct view, the light arriving at a point of observation differs for both eyes. Binocular disparity can therefore be regarded as an enrichment of the optic array since the light arriving at the viewpoint of the observer now more closely represents the light arriving at a point of observation. Stereoscopic video techniques make it possible to depict spatial information. The technical principles range from systems based on shutter glass techniques through head mounted displays to auto-stereoscopic systems [Zobel 1993, Griffin 1995, Lange 1993, Becker *et al.* 1992]. With the exception of auto-stereoscopic systems, stereoscopic systems require the user to wear additional devices such as red-green glasses, LCD glasses or small LCD monitors.

McLaurin *et al.* [1990, Jones *et al.* 1991] describe a stereoscopic laparoscope based on alternating frame and shutter glass technology. The laparoscope consists of two-rod lens systems which both have a built-in liquid crystal shutter (Fig. 3.9). Using alternating frame technology sequentially, the left and the right image are shown on the monitor at high frequency (100 Hz). The surgeon wears active liquid crystal shutter glasses. The glasses obstruct the view of the left eye when the image for the right eye is displayed on the monitor and vice versa. Because the image quality also depends on the diameter of the lens system, a disadvantage of a laparoscope based on dual-rod lens systems is the reduced resolution. The two lens systems used have smaller diameter compared to a single-rod lens system, and therefore have less light transmission and provide an image with lower resolution.

Griffin [1995] describes a stereoscopic system which makes use of a single-rod lens. An optical coupler splits the image at the exit of the laparoscope by means of a prism and a mirror-set (Fig. 3.10-top). Wenzl *et al.* [1994] describe a similar approach which makes use of a device that contains two microchip cameras (Fig. 3.10-bottom). The advantage of these systems is that a conventional laparoscope can be used to obtain binocular depth cues. However, the disadvantage is that the effect of these depth cues is reduced because the disparity is smaller than in a conventional stereoscopic laparoscope [Griffin 1995].

Apart from alternating-frame technology the left and the right image can also be separated using anaglyph techniques or systems based on polarisation [Becker *et al.* 1993]. Anaglyph techniques make use of colour coded images

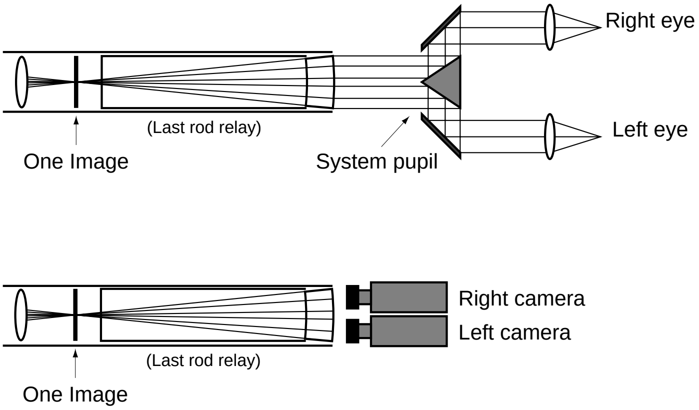

Figure 3.10
Splitting the image by using a prism and mirror set (top) [after Griffin 1995], and splitting the image by using two microchip cameras (bottom) [after Wenzl et al. 1994].

(red/green for instance). Both images are presented simultaneously on the monitor screen and the surgeon has to wear spectacles of the corresponding colours. Since colour is used to code the left and the right image, only grey reproduction is possible. Polarisation can also be used to separate the left and the right image. The surgeon has to wear spectacles of correspondingly polarised glass. For example, when the left image is polarised horizontally and the right image is polarised vertically the left glass of the spectacles will be polarised horizontally and the right glass will be polarised vertically. There are two technical set-ups possible: a dual monitor set-up or a single monitor set-up. The first set-up has two monitors which are adjusted to an angle of 90˚. The monitors are covered with vertical and horizontal polarising filters. A half-silvered mirror is placed at an angle of 45˚ to both screens. The second set-up makes use of an active polarisation screen mounted directly on a monitor which displays at high frequency. The image will subsequently be polarised horizontally or vertically [Becker *et al.* 1993, Mitchell *et al.* 1993, Pichler *et al.* 1996].

3.3.4 A point of observation with control

When a point of observation is implemented and the observer is provided with control, the spatial layout is specified and the observer can relate it to his viewpoint. There are two approaches to specify the point of observation relative to the viewpoint of the observer; either by displaying a point of observation for each possible position of the observer, or by tracking the position of the observer and displaying only the corresponding point of observation.

Systems that do not track the position of the user will have to display different information for each position. There are a number of technical implementations which make this possible, such as computer generated holographic systems [Benton, 1987] or volumetric laser displays, [Williams *et al.* 1991].

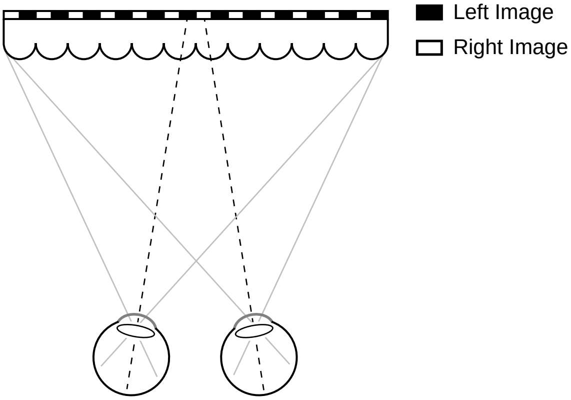

Figure 3.11
Auto-stereoscopy using a lenticular screen.

A volumetric laser display consists of a fast rotating or alternating screen. For each position of the screen a different image is displayed which together, because of the high rate at which the screen rotates, forms a three-dimensional image. The observer can select his position relative to this three-dimensional image, and observe it from different angles.

Other examples are auto-stereoscopic systems, which also provide different information for each position. Little *et al.* [1994] use an array of small liquid crystal televisions (LCTV) with corresponding perspective views in combination with a Fresnel lens. The Fresnel lens ensures that for each position only one of the LCTVs is seen. Börner [1987] describes an auto-stereoscopic system based on a lenticular screen (Fig. 3.11). To use a lenticular screen, the images from a number of points of observation have to be divided into vertical stripes and placed in alternating order. The lenticular screen is positioned in front of these stripes and ensures that for each position of the observer one image is observed (or two for stereoscopy).

The advantage of auto-stereoscopic systems is that more than one person is provided with spatial information. Only some of such systems are being applied to endoscopy or laparoscope. For example, Coquoz *et al.* [1993] and Podbielska [1993] apply holographic techniques to numerically reconstruct holographic images of the stomach using an endoscope. Dodgson *et al.* [1995] describe an auto-stereoscopic system based on an array of cameras and a

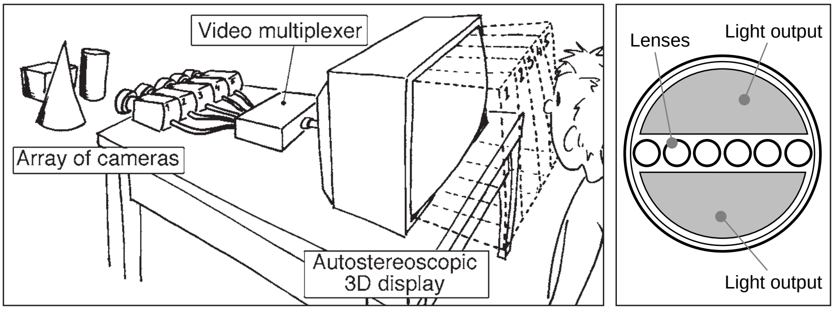

Figure 3.12
An auto-stereoscopic system based on an array of cameras (left) and its implementation for laparoscopy (right) [After Dodgson et al. 1995].

directional modulator (Fig. 3.12). Each camera obtains a different view of the scene and the directional modulator ensures that each view is only visible in a distinct area in front of the screen. The result of this is that each eye obtains a different view of the scene. They propose a laparoscope based on this system consisting of six different image guides (inset of Fig. 3.12).

Systems that track the position of the user only have to display the point of observation corresponding to the current position. An example of such a technical implementation is the Fish-Tank system [Ware *et al.* 1993]. This system works on the principle that the monitor is a window to a virtual environment or to a remote site. Based on the position of the observer the monitor shows an image that depicts a view for only this position of the observer, similar to the anamorphic picture shown in Fig. 2.6. This Fish-Tank system can be applied to computer generated images as well as camera images. When applied to computer generated images, for each position selected by the observer a corresponding anamorphic picture is calculated. This technique is used by DeFanti *et al.* [1993] to create a CAVE (Computer Assisted Virtual Environment); an immersive virtual environment in which the observer can freely walk around without wearing a helmet mounted display. CAVE basically is a room of which the walls, floor and ceiling are replaced by back projection screens which display an anamorphic picture in accordance with the viewpoint of the observer. For the observer the anamorphic pictures depict a three dimensional environment inside the CAVE. Djajadiningrat *et al.* [1997a, 1997b] use a similar approach to create Cubby, a multi-screen movement parallax display which can be used for direct manipulation (Fig. 3.13). Cubby consists basically of a small open cube (20x20x20 cm) of which the three remaining sides are replaced by back projection screens. As in CAVE, these screens display an anamorphic projection based on the viewpoint of the observer. The advantage of Cubby is that it allows direct manipulation of virtual objects in a desk-top set-up.

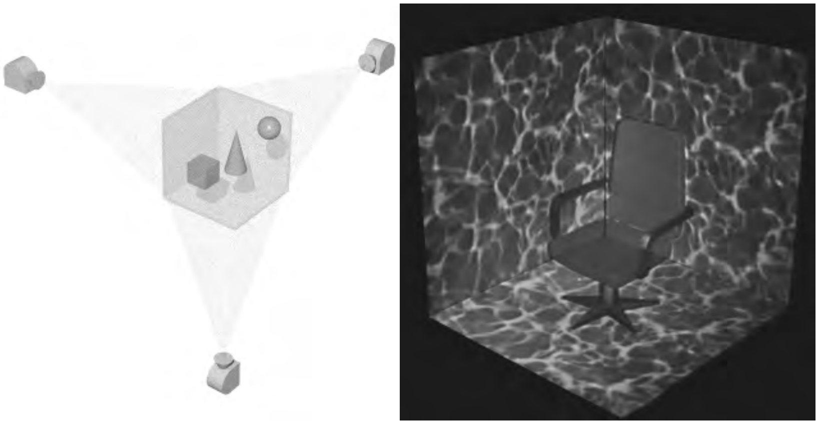

Figure 3.13
An overview of the three projectors and Cubby (left) and a chair shown inside Cubby (right).

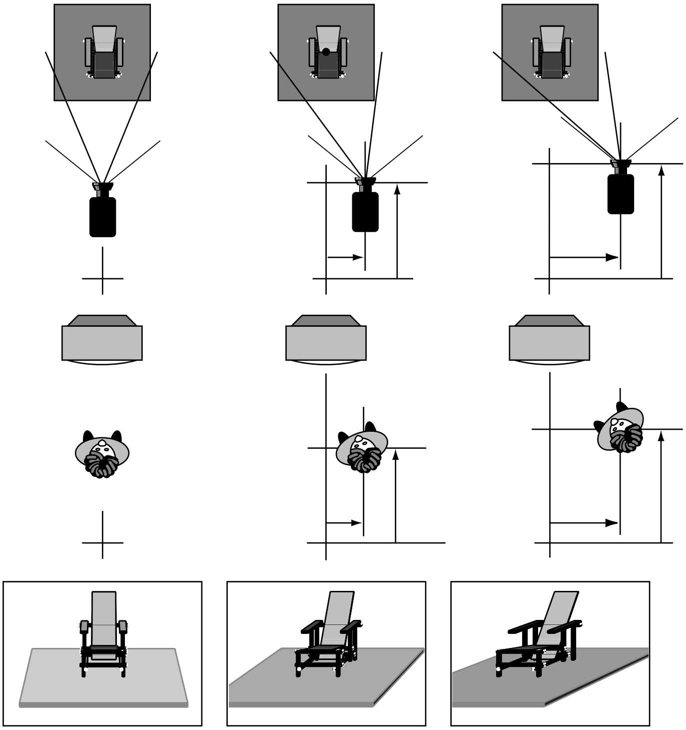

Figure 3.14
The principle of the fish-tank system (top) and the images displayed on the monitor for different viewpoints (bottom).

The Fish-Tank system can also be applied to camera images but this is more difficult compared to computer images since it requires a camera with a large viewing angle and a device to obtain the required cut-out of the camera image (Fig. 3.14). Furthermore, as can be seen from Fig. 3.14-bottom, the distortions imposed by the manner in which the camera moves become more apparent [Pasman, 1997]. The image is displayed in normal perspective only for the observer who is tracked. Therefore it is less suitable for multiple users.

Other systems that specify the point of observation relative to the viewpoint and provide control over the selection of the point of observation are immersive virtual reality (VR) systems. An immersive VR-system requires the user to wear a helmet containing two miniature LCD monitors. These monitors display a view of a virtual environment. The location and the orientation of the user are recorded and when the user moves the images displayed in the helmet change accordingly. This allows a user to explore the virtual environment. Such systems are often suggested as applicable to tele-surgery [e.g. Pieper *et al.* 1991, Satava 1993, Taubes 1994, Brown *et al.* 1994]. Green *et al.* [1995] describe a robotic system where the surgeon operates a surgical robot from behind a console; they use VR techniques to restore eye-hand co-ordination to something that more closely resembles open surgery. Poor eye-hand co-ordination, however, is caused not only by the limitations imposed on manipulation by the trocars, but also by the poor design of laparoscopic instruments. Basically these instruments are no more than extruded scissors. Restoring eye-hand co-ordination therefore may be achieved equally well, or even better, by redesigning laparoscopic instruments to fit the action possibilities during laparoscopic surgery [e.g. Herder *et al.* 1997].

It remains debatable whether VR technology is needed in the operation theatre. As discussed in the introduction (Ch. 1), the main difference between open surgery and laparoscopic surgery is that the surgeon has to rely solely on instruments. During conventional surgery, visualisation of the workspace does not rely on a monitor image, and the surgeon can feel the tissue with his hands. During laparoscopy, the instruments determine most of the visual and haptic information that is obtained. Additionally, the surgeon can see the light of the laparoscope shining through, and he can feel the abdomen wall. In VR systems the information the surgeon is provided with depends entirely on the technical implementation. Apart from whether it is possible, technically, to provide the surgeon with all the information that is needed, the feasibility of VR systems also depends on whether it is known what information the surgeon needs. Some studies are reported on analysing laparoscopic operation. For example, Dominguez [1997, 1995] uses interview techniques to analyse what visual information makes surgeons transfer from laparoscopy to open surgery. Claus *et al.* [1995, Sjoerdsma 1998] use time-measuring techniques to analyse the effort to perform manipulations. Studies in which such approaches are combined, i.e. studies which link the effort to perform manipulations and the provided visual information, may reveal what information is needed when performing a manipulation task using a VR system. Even when this is known, it remains debatable whether more technology has to be placed between the surgeon and the patient. Instead, technical developments should focus on improving the information that can be obtained with current laparoscopic operation techniques.

3.4 Discussion and conclusions

In this chapter two criteria for classification of 3D systems were proposed to compare various implementations on how the spatial layout is specified. These criteria were identified based on analysis of the tasks to be performed during laparoscopic operation, namely observation and manipulation tasks. Observation tasks require the specification of the spatial layout and manipulation tasks require the specification of the spatial layout relative to the observer. The first criterion refers to how the spatial layout is specified relative to the point of observation. The point of observation is the location of the tip of the laparoscope. Specification of the spatial layout can either be based on static depth cues, in which case the position of the point of observation is specified, or it can be based on kinetic depth cues, in which case the movement of the point of observation is specified. The second criterion concerns the specification of the relation between the point of observation and the viewpoint of the surgeon. This relation can either be specified by movements of the instruments relative to the laparoscope, or by movements of the laparoscope. When the surgeon has no control over the point of observation, the relation is specified by movements with the instruments. When the surgeon has control over the point of observation, the relation is specified by movements with the laparoscope. Table 3.1 gives an overview of the criteria.

Based on the criteria, various 3D systems described in the literature were discussed. From this it can be concluded that most technical implementations applied to laparoscopy focus on improving depth perception for the situation where the surgeon has no control over the point of observation. These technical implementations range from removing flatness cues and adding motion parallax to providing stereoscopic information. Having no control, the surgeon cannot relate the point of observation to his viewpoint, and he is forced to deduce it from the movements of the instruments. As the relation between the point of observation and the viewpoint changes with each movement of the laparoscope, deduction is an ongoing process. Robotic supports are suggested to minimise these movements of the laparoscope, and to provide the surgeon with discrete control over the point of observation, i.e. the surgeon can select a new point of observation but does not have continuous control. However, the point of observation and the viewpoint continue to be related only by means of movements with the instruments. To relate them by means of visual information the surgeon must be made an active observer, i.e. he must be provided with direct continuous control over the laparoscope.

There are two ways to make the surgeon an active observer. First, by specifying movement through the implementation of kinetic depth cues. This will specify the change in point of observation for each change in the position of the surgeon. Second, by specifying a position through the implementation of static depth cues. This will specify the point of observation for each position of the surgeon. The difference in specifying a changing point of observation and a point of observation is the effect it may have on manipulation. When a changing point of observation is specified, then the change in point of observation relative to the instruments is coupled to the change in viewpoint relative to the instruments. Then directions, like upwards and downwards, are related to the instruments and since the instruments are held by the surgeon, directions are related to the surgeon. When a point of observation is specified, then the point of observation inside the abdomen is linked to the viewpoint outside the abdomen. This suggests a one to one correspondence between the viewpoint of the surgeon and the point of observation displayed on the monitor. It creates the illusion of the image being rigidly connected to the border of the monitor. As a result, since the abdomen appears to be rigidly connected to the monitor, moving an object upwards appears to be directed towards the top of the monitor. This rigid connection between the monitor and the displayed image imposes a similar connection between the instruments displayed on the monitor and the instruments held by the surgeon. It suggests a correspondence between the directions of the displayed instruments inside the abdomen and directions of the instruments outside the abdomen.

Implementing a changing point of observation can be combined with the specification of a point of observation. However, such a combination may not always prove to be an advantage. For example Cole *et al.* [1991] investigated the advantage of combining movement parallax with either stereoscopic or monoscopic vision, for performing a manipulation task. Apart from finding that stereoscopic vision results in the best performance, they found that movement parallax combined with stereoscopic vision did not improve performance compared to stereoscopic vision alone, whereas combined with monoscopic vision movement parallax did improve performance. Thus, manipulation tasks require either binocular information or control over the point of observation. This research focuses on providing the surgeon with control over his point of observation.

The next chapter will describe an experiment investigating the advantage of providing the surgeon with control over his point of observation.

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[1] Magnetic Resonance Imaging (MRI) is a technique which utilises the magnetic properties of particles to visualise a patients internal structure. This technique especially is useful for the visualisation of soft tissue.

CHAPTER 4

VIEWPOINT PARALLAX

Creating shifts by moving a camera

This chapter is an adapted version of:

Voorhorst, F.A., Overbeeke, C.J., & Smets, G.J.F.
Using movement parallax for 3D laparoscopy.
Medical progress through technology 1997;21:211-218

4.0 Introduction

In Chapter 3 it was concluded on the basis of theoretical considerations that the surgeon, during laparoscopy, should be made an active observer, i.e. an observer who has active control over his visual information. Currently, this is not the case since the laparoscope is controlled by an assistant. Therefore, the perception-action coupling is hampered for the surgeon and estimates of sizes and distances are based on pictorial depth cues and (passive) motion parallax, rather than (active) movement parallax. By implementing the DVWS for laparoscopy, and thus by coupling the head movements of the surgeon to the motions of the tip of the laparoscope, the perception-action coupling will be restored. This allows the surgeon to explore and obtain spatial information through movement parallax.

In this chapter two questions will be addressed concerning the feasibility of the DVWS for laparoscopy. First, the question arises whether performance will increase when subjects obtain spatial information from movement parallax under laparoscopic viewing conditions and, secondly, we need to know how large the movements made by the subjects are when the motions of the tip of the laparoscope are linked to their head movements. These questions were investigated in a laboratory experiment. Laparoscopic viewing conditions were mimicked by using a small fibrescope and head movements were registered during the experiment. These movements give an indication of the camera motions required in the final product.

Figure 4.1
An example of a knot placed in front of the dead end tube shown from the left, middle and the right.

4.1 Method and Materials

4.1.1 Task and stimuli

Pilot experiments showed that subjects do not move their head while performing a manipulation task. When performing a pinpointing task, for example putting a thread through the eye of a needle, people tend to concentrate and sit as still as possible. The only movement will be the thread approaching the eye of the needle. When performing an observation task, for example when inspecting an object from different sides, people naturally make head movements. Therefore, the experiment was divided into two parts, an observation part and a manipulation part.

As stimuli, knots made out of three wires were used. Although they may only vaguely resemble a real situation, e.g. the identification of a vein, these knots have the advantage they encouraged subjects to explore. Fig. 4.1 shows an example of a stimulus. The root of each wire, visible at the lower end of the monitor, was labelled with a colour. Below the monitor were three small lights of which the colour and the position corresponded to the colour and position of the labels. Each wire ended in a small sphere towards the upper end of the screen. Above the screen there were three buttons, each corresponding to one of the spheres. Fig. 4.2 gives an overview of the set-up. The stimulus was placed in a dead end tube, simulating the inside of the intestine. The inside of the tube was covered with a grid to obtain a texturally rich environment which provides shifts within the image during observer movements.

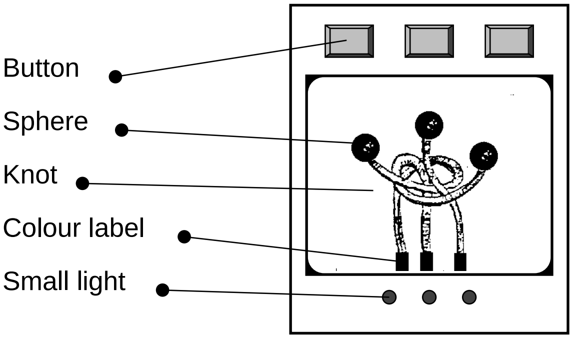

Figure 4.2
Overview of the monitor with the buttons and the small lights.

The manipulator used was a lever, with four degrees of freedom: one translation and three rotations (Fig. 4.3). When the manipulator was pushed forwards, the tip of the manipulator also moved forwards. However, when the manipulator was lifted, the tip of the manipulator moved downwards and when the manipulator was pushed to the right, the tip of the manipulator moved to the left. These movements correspond to the movements of a manipulator during laparoscopic operation. The distance over which the manipulator had to be moved was approximately 4 cm.

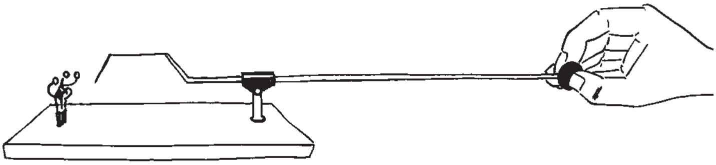

Figure 4.3
The manipulator used during the experiment.

The observation task was to solve the knot, i.e. the subject had to select the sphere connected to the wire indicated by a coloured light below the monitor (Fig. 4.1). This was done by the selecting the button above the monitor which corresponded to the selected sphere. The manipulation task was to move the manipulator towards the sphere that had been chosen in the observation part, and to touch it. Subjects were asked to perform both tasks as well and as quickly as possible.

4.1.2 Hypotheses

There are three dependent variables, namely performance on the observation task, the time used performing the observation task, and the time used performing the manipulation task. The performance of the manipulation task is not an independent variable, since touching the sphere which was chosen during the observation part is always performed correctly.

First, the active subjects were expected to perform the observation task better than the passive subjects (active and passive observers are discussed in Chapter 2). The null hypothesis and the alternative hypothesis are: H_0: $\mu_a \leq \mu_p$, and H_1: $\mu_a > \mu_p$, where μ stands for the mean number of correctly solved puzzles, and subscripts a and p stand for active and passive subject.

Second, the active subjects were expected to use more time to perform the observation task since they have the ability to scrutinise the knot, thus H_0: $\tau_{1a} \leq \tau_{1p}$, and H_1: $\tau_{1a} > \tau_{1p}$, where τ_1 stands for the mean time needed to perform the observation task.

Third, the active subjects were expected to use less time performing the manipulation task since they have the ability to obtain more spatial information during the observation task, thus H_0: $\tau_{2a} \leq \tau_{2p}$, and H_1: $\tau_{2a} > \tau_{2p}$,where τ_2 stands for the mean time needed to perform the manipulation task.

4.1.3 Independent variables

During the experiment the performance of two groups of subjects was compared: active and passive observers. Seventeen subjects were randomly divided over the two groups. A total of 9 active subjects controlled the camera motions with their head movements, 8 passive subjects viewed a static image. All subjects were students from the Faculty of Industrial Design Engineering. The experiment took about half an hour for each subject.

The subject's selection and the time they needed for performing the observation task as well as the time needed in performing the manipulation task were registered. To get a better insight of the head movements of the subjects during exploration, the movements of five subjects were registered.

4.1.4 Procedure

The experiment consisted of three rounds with two tasks, observation and manipulation. In each of the three rounds ten trials were performed. In each of the ten trials one knot was presented. A total of ten different knots were used, which were presented in random order within each round. Each trial started with the observation task. At the beginning the screen was black, as the scene was not illuminated. The observation task started as soon as the scene was illuminated. Simultaneously, a coloured light below the monitor indicated which wire had to be followed. The subject, after finding the sphere that was connected with the wire to be followed, had to press the corresponding button above the monitor. The observation task ended when a button was pressed. The sphere that was selected had to be touched with the manipulator. This was the manipulation task. Touching the sphere made the monitor turn black and ended the trial.

Prior to the experiment the subjects were allowed to practise. Two knots, which were not used in the experiment, were used as stimuli for practice. The first knot was simple and illustrated the tasks to be performed. The observation task and the manipulation task were practised on this knot ten times. The second, more complex knot illustrated the complexity of the knots used during the actual experiment. This knot was practised on twenty times. While the observation task was easily learned, the manipulation task required much practice. During practice, subjects spent most time on improving their control over the manipulator. To test their control over the manipulator, the subjects were asked to touch a specific sphere. If, according to the experimenter, touching the sphere with the manipulator was fluent (fast, with confidence), the subject was allowed to start the experiment. If touching the sphere with the manipulator proved difficult the subject had to practise more. This was repeated until the subject had proven his ability to move the manipulator smoothly. The conditions during practice were equal to the conditions during the experiment.

4.1.5 Apparatus

A prototype for medical laparoscopy based on the DVWS was built (Fig. 4.4). The size and direction of the motions to be made by the camera are unknown, they can however be estimated from unrestricted movements of the subjects. Therefore the prototype was designed for larger motions than those allowed by the dimensions of currently used laparoscopes.

There are three directions of movement when an observer moves freely around a fixation point: one horizontal and vertical rotation, and one horizontal translation to and from the fixation point. The corresponding camera motions are illustrated in the inset of Fig. 4.4. The prototype allows horizontal and vertical rotations up to 60˚. The horizontal displacements to and from the fixation point may vary between 5 mm and 30 mm relative to the centre

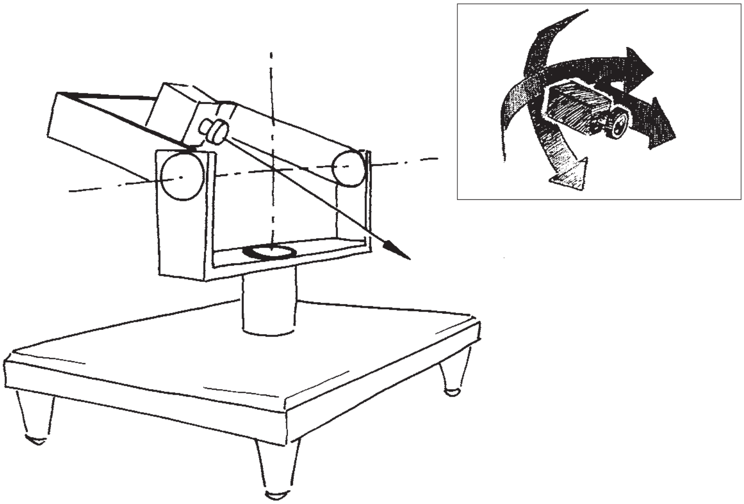

Figure 4.4
Prototype of the laparoscope. The inset shows the movements the camera can make.

of the screen. These displacements are large compared to the expected movements of the observer. The movements of the subjects were restricted since the subjects were seated on a chair. A subject seated on a chair can be compared with a pendulum standing up side down. A person with a chair-to-head length of 1 m, seated at a distance from the monitor of 0.8 m, causes a rotation of the camera of 52˚ when he moves sideways by 90˚ (i.e. the upper body in a horizontal position). Such a tilt is unlikely to occur and camera rotations up to 60˚ seem sufficient. The distance towards the fixation point of the camera in this prototype is comparable to the focus distance of a laparoscope based on binocular disparity (20 mm), [McLaurin *et al.* 1991].

The prototype used a fibrescope (Olympus XPF-21-IG). The advantages of using a fibrescope for the experiment were its size (2 mm diameter) and flexibility. The image was registered by a colour camera (ELMO EM-102 PAL) and displayed with about 7 times magnification (the size of the stimuli was about 3 cm and the size of the projection was about 20 cm) on a 20” colour monitor. In order to couple the movements of the subject to the motions of the camera, the head position of the subject was measured by means of a helmet connected to a construction consisting of three rods (Fig. 4.5). To detect the subject's head displacement in three directions the change in orientation of each rod was measured using a 500 steps encoder.

Head movements of five subjects were registered independently from the apparatus used for the experiment set-up. To register these movements an infra-red detection system was used, which could measure the position of a small reflective disc on the forehead of the subject (DynaSight, resolution of 0.1 mm for a 7 mm target at 80 cm under normal fluorescent room light).

Figure 4.5:
Coupling between the camera and the head of the observer during the experiment.

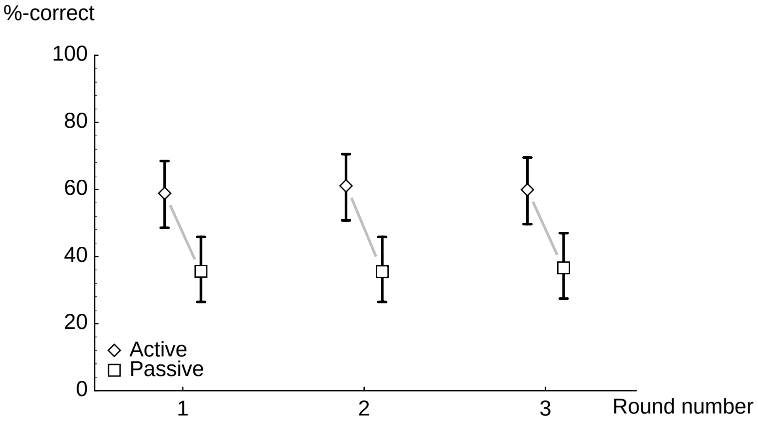

Figure 4.6
Number of correctly solved knots for the observation task (95%-confidence intervals). During all rounds, the performance of the active observer is better than the performance of the passive observer.

4.2 Results

4.2.1 Experiment

The results in terms of correctly solved knots, the time used for the observation task and the time used for the manipulation task (mean and 95% confidence intervals) are shown in figures 4.6 and 4.7. These figures show that active subjects perform better than passive subjects on the observation task (t-test, $p<0.001$). It was expected that active subjects would use more time performing the observation task. This was found for the first round and the second round (t-test, $p<0.01$),but no difference in amount of time used was found for the last of the rounds (Fig. 4.7).

In contrast with the expected results the active subjects did not perform the manipulation task faster than the passive subjects (Fig. 4.8). There is a learn-

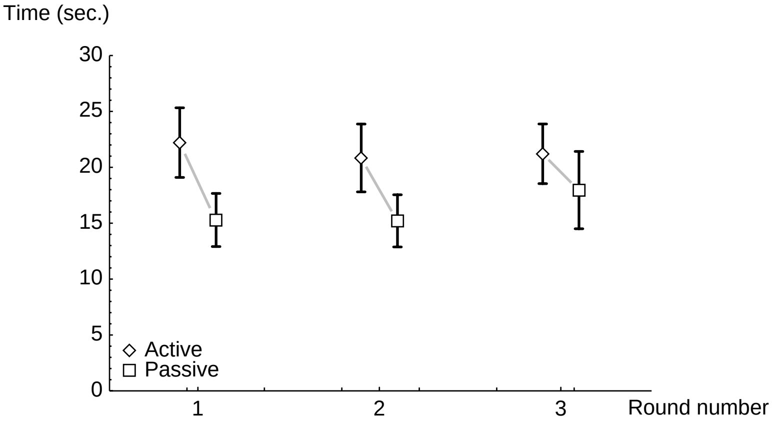

Figure 4.7
Time used for performing the observation task (95%-confidence intervals). During rounds 1 and 2 the passive subjects perform faster than the active observers.

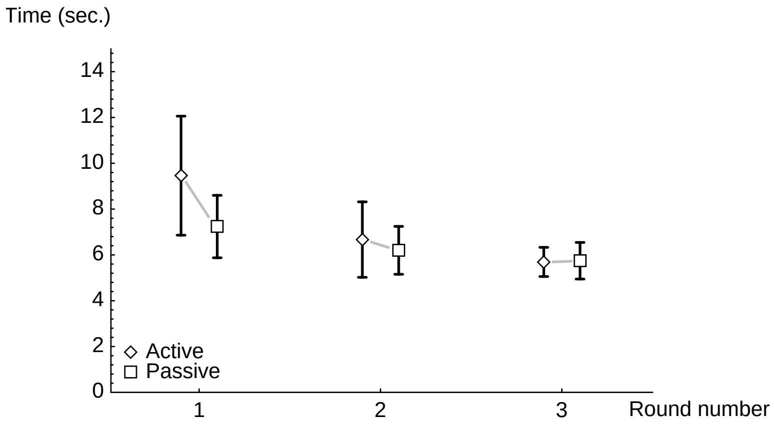

Figure 4.8
Time used performing the manipulation task (95%-confidence intervals). Only in the first round perform the active observers more slowly than the passive observers.

ing curve visible in Fig. 4.8, showing that active subjects performing the manipulation task improved with each series. In the first round, active subjects used more time to perform the manipulation task than the passive subjects. In the last round no difference was found between active and passive subjects.

4.2.2 Movements during exploration

The head movements registered with the infra-red detection device showed, for the horizontal direction parallel to the monitor screen, a mean position of +5 cm relative to the centre of the screen with standard deviation of 11 cm. Minimal and maximal positions recorded were -42 cm (to the left) and 34 cm (to the right). A position of 40 cm relative to the centre of the screen corresponds to viewing the object at an angle of 26°. The small but not significant difference from zero off-set shown by the data may be caused by the position of the manipulator. The manipulator was positioned on the right side of the subjects. Since the manipulation task was performed directly after the observation task, the subjects were invited to start and stop the observation task while leaning to the right.

Movements of subjects can be divided into steps. A step is defined as the distance between two turning points, i.e. a point where the velocity changes sign. It is assumed that there are two reasons for a step to occur: either the subject selects a new angle of observation, or the subject proceeds with further explorations around a selected angle of observation. Selecting a new angle of observation is expected to result in a small number of bigger steps, whereas further exploration is expected to result in a larger number of smaller steps. During a laparoscopic operation the angle of observation would be selected by moving the entire laparoscope, whereas the smaller movements around the selected point of observation would be made by the tip of the DVWS-based laparoscope. The small movements during the observation task of the experiment are an indication of the minimally required camera motions in a production version of a DVWS-based laparoscope.

During the experiment 500 steps encoders were used for coupling the head movements to the camera motions. With this resolution movements smaller than 0.72° did not influence the motion of the camera. The distance towards the screen being 0.8m, this translated to head movements smaller than 1 cm not being registered. In Fig. 4.9 the sizes of steps made during exploration are displayed on the horizontal axis and the number of times these steps appear is given on the vertical axis. The steps made in the X-direction show a peak at steps of 10 cm. The same peak is visible for the steps made in the Z-direction, but not for the steps made in the Y-direction. While the observation task invited movements in all three directions, the sizes of movements in the Y-direction are smaller (seated subjects) compared to the sizes of movements in the X- and Z-direction. The movements made by the subjects are mainly in a horizontal plane.

Both the X-direction and the Z-direction show a decrease in the number of times a step occurs as the step size increases, and a peak at a step size of 10 cm. This peak indicates a preference for this step size, and therefore can be used as estimate for the minimal required camera motion. A step size of 10 cm corresponds to an angle of 7° if the head-to-screen distance is 0.8m. The largest required horizontal motions of the camera is 2.5 mm off centre (i.e. 5 mm in total), when the lens-fixation point distance is equal to 20 mm.

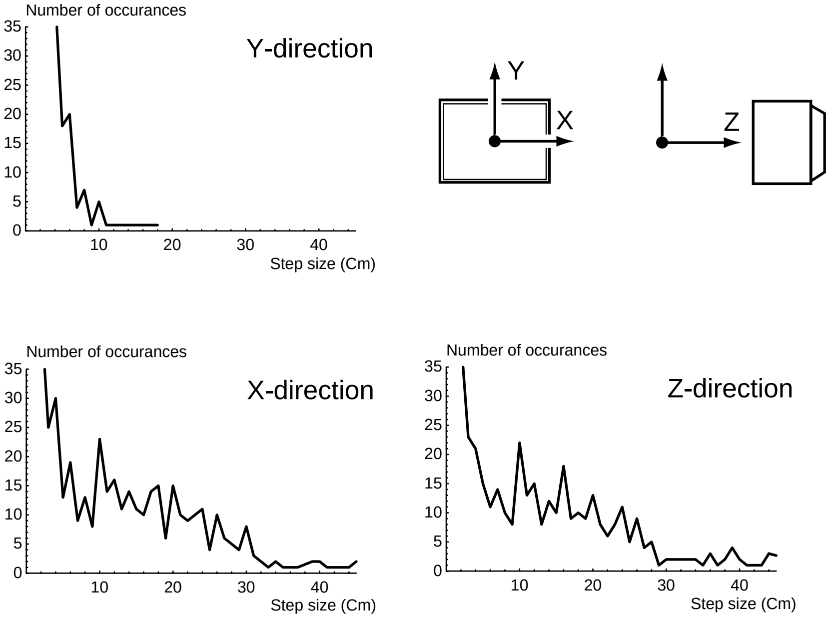

Figure 4.9
Number of occurrences of step sizes for the different directions.

4.3 Discussion and conclusions

Two questions were investigated to determine if the principle of movement parallax is technically implementable for medical laparoscopy. Does performance improve when assisted by the DVWS for laparoscopic viewing conditions, and if so, how large are the movements made by the observer?

The first question, the usability of movement parallax (the DVWS) for obtaining depth perception during laparoscopy was investigated in an experiment. The experiment consisted of two parts, an observation and a manipulation part. The results, better performance of the active subjects over the passive subjects, show the advantage of the DVWS for observation tasks. Ware *et al.* [1993] used the same type of observation task we used in our experiment. They asked subjects to indicate to which of two interwoven trees a leaf belonged. They also found that head-coupled movement parallax is of great importance during observation tasks. The results of the manipulation task indicate that active subjects experience a scaling of the visual information. The (unknown) size of the knot is smaller than the shown size on the monitor image. The coupling between the shifts within the monitor image to the head movements of the subject causes the subjects to accept the shown size of the knot as its real size. The shown size suggests larger movements with the manipulator. However, since the actual knot is much smaller, the movements with the manipulator must be small and the active subjects need to adjust and to learn a scaling factor in order to successfully carry out the manipulation task. This scaling factor was not learned during the practice trials, since the subjects were shown only two knots. Once the active subjects had solved the knot the motivation to explore disappeared. Because of the lack of motivation to explore, the active subjects did not move during practice and the size of the knot was not related to head movements. Passive subjects do not control the camera motions and are therefore not confused by the scaling of the visual information. The active subjects have to learn to adjust to this scaling factor, but have the advantage of obtaining more depth information.

For the second question, the sizes of movements made by the observer during the experiment were analysed. This analysis shows two aspects. First, the movements are small enough with regard to the size of a laparoscope. A laparoscope commonly has a diameter of 10 mm. McLaurin *et al.* [1991] concluded that for a stereoscopic laparoscope a focal distance of 20 mm is sufficient. The minimal space needed for movements of the optical fibre is found to be 2.5 mm for a lens-fixation point distance of 20 mm. Second, the movements made are mainly horizontal. The same may hold for laparoscopic operation. Surgeons perform laparoscopic operation standing up, which limits their ability to move vertically (up and down). Motions away from and towards the fixation point may not have to be implemented because of the ability to move the laparoscope in this direction. Based on these results it is sufficient for the tip of an DVWS-based laparoscope to allow movements only in the horizontal plane, parallel to the monitor.

The experimental set-up differs from the practical situation in two aspects, both of which may cause smaller differences in performance between active and passive subjects in a more realistic set-up. First, during the experiment the laparoscope was fixed on a stand preventing the passive observer from perceiving any parallax shifts on the screen. During operation, however, the laparoscope is held by an assistant whose small, mainly low frequency movements result in parallax shifts on the monitor. These parallax shifts, which are not controlled by the observer, are called passive parallax and provide for (limited) depth information. Second, the resolution of the fibrescope used during the experiment was less than the resolution of a laparoscope used in practice. Low resolution hinders the passive subject more than the active subject [Smets and Overbeeke, 1995]. For example, Pasman *et al.* [1997] found a trade-off between image quality (resolution and number of grey-levels) and camera range; the ability to explore (select a point of observation) compensated for reduced image quality. This suggests that when the resolution of the camera increases, the difference in performance of active and passive observers reduces. However, even with high resolutions being an active observer may be an advantage over being a passive observer. For example, Smets *et al.* [1987] describe an experiment comparing the performance of active and passive subjects in a manipulation task. Both groups of subjects were asked to align a set of wedges. While the resolution of the video camera used was higher than the resolution of the image during our experiment, they found a difference between active and passive subjects performing this manipulation task.

By using the DVWS the surgeon would partly regain control over the camera motions. This does not render the assistant superfluous. The motions of the camera during exploring, according to the principle of the DVWS (Fig.

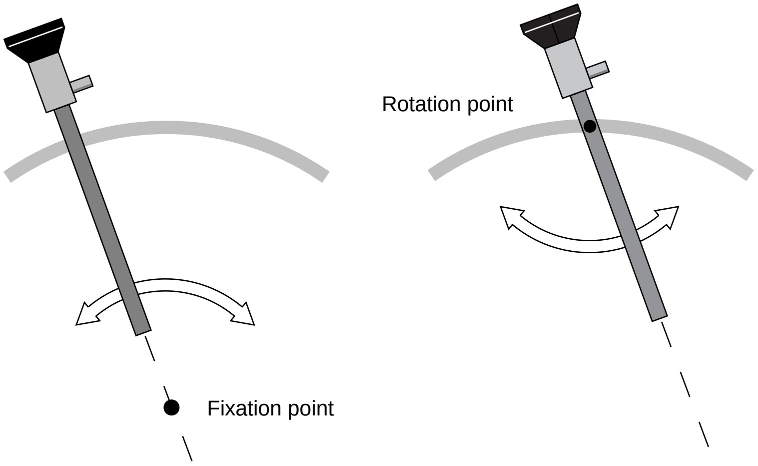

Figure 4.10 *The movements of the laparoscope corresponding to the DVWS (left) and the movements of the laparoscope made by the assistant (right).*

4.10-left), differ from the motions made while changing the viewpoint (Fig. 4.10-right). To select a viewpoint, the whole laparoscope has to be rotated around the point where it enters the abdomen. The assistant may still be needed for directing the laparoscope (Ch. 6). Also, adding the DVWS might improve communication between the surgeon and the assistant. Now, the assistant has to follow the surgeon's instruments and, preferably, has to anticipate the surgeon's actions. If the assistant's actions do not match with the surgeon's wishes, the surgeon can correct verbally, but he can also take over the laparoscope. Coupling the tip of the laparoscope to the movements of the surgeon may make it easier for the assistant to follow the surgeon, so he may then be able to anticipate the surgeon's actions.

From the results of the experiment described in this chapter, it is concluded that the DVWS is feasible for laparoscopy. Implementation is especially suitable for observation tasks since they invite observers to explore and move their head. For manipulation tasks, however, implementing the DVWS might not be feasible since these tasks invite observers to sit still (Ch. 6). The main problem for implementation is the technical realisation. Generating parallax shifts by moving the tip of the laparoscope requires a complex mechanism. Therefore, the next chapter will explore a different way of generating shifts on the monitor screen, namely by using a moving light source, called shadow movement parallax.

SHADOW PARALLAX

Creating shifts by moving a light source

5.0 Introduction

Based on theoretical considerations, it was proposed that during laparoscopic operation the surgeon should be an active observer (Ch. 3). This was investigated in an experiment described in Chapter 4. The results of this experiment indicated that making the surgeon an active observer may not have advantages when performing a manipulation task, but does have advantages when performing an exploration task. Applicability, however, is difficult since it requires a complex mechanism inside the laparoscope. Therefore, in this chapter a simple method of creating shifts within the monitor image is investigated, namely by using a moving light source. This is called shadow parallax.

This chapter starts with a description of the principle of shadow parallax. This principle is then investigated in three experiments: Experiments 2 to 4. In Exp. 2 shadow parallax and viewpoint parallax are compared. In Exp. 3 the feasibility of a technically simple implementation of shadow parallax is investigated, namely simulated shadow parallax. In Exp. 4 the feasibility of simulated shadow parallax is again investigated, but now using more complex stimuli. In the discussion the results of the experiments are examined.

5.1 Creating shifts by moving a light source

In Chapter 4 it was concluded that the DVWS is applicable to exploration tasks under laparoscopic viewing conditions. Perceptually, implementation is feasible since the performance of an observation task improves when allowing for exploration. Technically, implementation is feasible since the explorative head movements are small enough for a small camera to follow these movements inside a laparoscope with a diameter of 10 mm. Such implementation, however, requires a complex mechanism inside the laparoscope

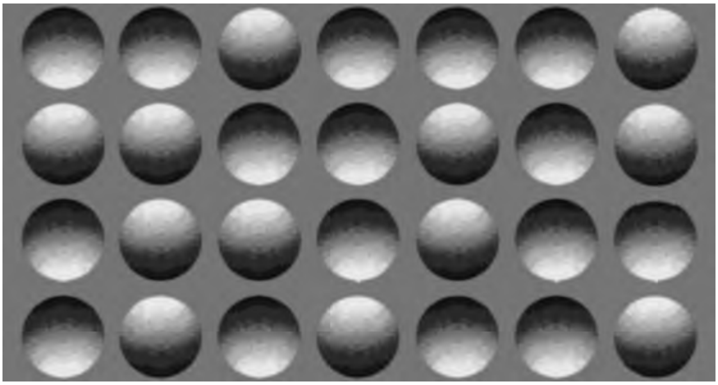

Figure 5.1
Depending on their shading these spheres are perceived as either convex or concave. Observing this picture upside down will make the previously perceived convex spheres look concave and vice versa [After Ramachdanran 1988].

(implementations are discussed in Ch. 7). A less complex mechanism may be needed when instead of the camera, a light source is linked to the head movements. A moving camera creates shifts within the monitor image which are similar to parallax shifts. Linked to the head movements of the observer, these shifts provide for body scaled information about the spatial lay-out of the observed scenery (Ch. 4). Shifts similar to parallax shifts may also be generated by moving a light source. This is called shadow movement parallax[1]. Before explaining the technical implementation of shadow parallax, the importance of shading and shadows in general will be discussed.

Shading and shadows are considered an important depth cue. The motion of the sun across the sky causes surfaces within the environment to be illuminated differently during the day. For example, surfaces which are under high illumination early in the day will be under low illumination late in the day and vice versa. This daily exchange between the lighted state and shaded state of a given surface is an important but little-noticed fact about the environment [Gibson 1979, p 30]. How the natural illumination of the sun influences perception is illustrated in Fig. 5.1, which shows a number of convex and concave spheres. Which of these spheres are perceived as convex depends on their shading. Our visual system tends to assume that there is one light source, and that the light comes from above [Ramachandran 1988]. Consequently, a sphere with a shaded lower half, will be perceived as convex, whereas a sphere with its upper half shaded will be perceived as concave. Rotating the page and viewing Fig. 5.1 upside down will make the previously apparently convex spheres appear concave and the apparently concave spheres appear convex. Ramachandran [1988] describes a number of examples similar to Fig. 5.1, illustrating the importance of shading for depth perception which, especially when the shaded surface is enclosed by an outline, conveys a convincing impression of depth. Norman *et al.* [1995] investigated the influence of shading, highlights and texture on the perceived shape of an object for stereoscopically and monoscopically viewed images, and for situations with or without observer movement. They found that deformations of shading and highlights are informative sources for optical information. Shaded or high-lighted objects, displayed moving or stereoscopically, appeared as compelling as textured objects. The importance of shading for depth perception is also shown by Bülthoff *et al.* [1988]. They investigated the integration of shape from shading combined with stereo and found that disparate shading (i.e. shading is provided stereoscopically while for example edges are not) yields a vivid stereoscopic depth perception, whereas non-disparate shading is a poor cue to depth. Blake *et al.* [1991] found that stereoscopically viewed specularities of a stationary light source provide a cue for 3D surface perception. The investigations mentioned make use of a stationary light source. Shadow parallax, however, makes use of a moving light source. Ramachandran [1988] describes a display that alternated rapidly between one frame showing a shaded convex object above a shaded concave one, and a second frame in which the objects are reversed. Subjects reported seeing a sphere jumping up and down between two holes in the background.

Moving a light source creates shading patterns deforming and shifting over a surface. The manner in which the these patterns deform depends on the structure of the environment and on the movements of the light source. Therefore, they potentially indicate the structure of the environment. For this to be true, subjects must be able to determine a spatial structure from shading and shadow deformations. In part this was demonstrated by Norman *et al.* [1994]. They found that subjects can determine an object's three-dimensional structure from deformations of shadows cast by several rotating objects in front of a stationary light source. The subjects were presented with elliptical objects on a monitor either in rigid motion (when the objects rotated together as a rigid configuration), or in non-rigid motion (when the objects rotated

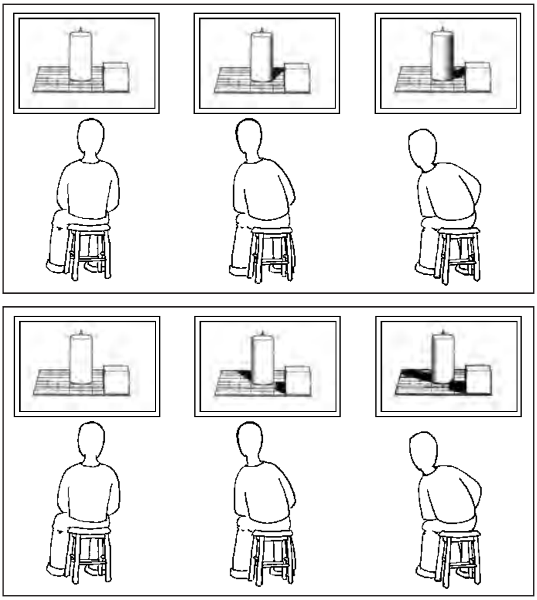

Figure 5.2
Two ways to link the light source to the head movements of the observer: the light source moves along with the observer (top), or the light source moves in the direction opposite to the observer (bottom).

around axes that differed in slant). They found that based on the deforming contours of the cast shadows the subjects could distinguish between rigid motion and non-rigid motion. An observer may be able to perceive the structure of the environment by actively moving the light source.

With the technical implementation that is called shadow parallax the light source is linked to the head movements of the observer. There are different ways to link the light source to the head movements of the observer (Fig. 5.2). For instance, either the light source can move along with the observer (i.e. when the observer moves to the right the light source moves to the right also) or it can move in the opposite direction to the observer (i.e. when the observer moves to the right the light source moves to the left). In the first situation, when the light source moves along with the observer, the shadows cast by an object upon a surface move in the direction opposite to the observer (Fig. 5.2-top). Comparing this to parallax shifts (objects in front of the fixation point shift in the direction opposite to the observer), the direction in which the shadows shift suggests they are located closer to the observer than the object by which they are cast. Since the shadows are further away than the object which casts them, it was decided that the light source was linked such that it moves opposite to the observer. Then, the shadows cast by an object upon a surface move along with the observer (Fig. 5.2-bottom). This corresponds to the parallax shifts generated by objects behind the fixation point.

With respect to implementation for laparoscopy, shadow parallax has the advantage over viewpoint parallax in that a moving light source can be simulated by two stationary light sources of which the intensity balance varies. For example, a light source movement to the right can be simulated by increasing the intensity of the right light source while simultaneously decreasing the intensity of the left light source. This technical implementation is called simulated shadow parallax. The process of increasing and decreasing the intensity of the light source may provide information about the shape of the surface. Within a homogeneous light field, points with equal luminance form lines across the surface (isophotes). Koenderink *et al.* [1980] calculated illumination of surfaces for a homogeneous light field, which showed that isophotes shift across the surface if the surface is rotated relative to the light source. Moving a light source relative to the object might create movements of the isophotes similar to rotating the object relative to the light source. Simulating a moving light source by increasing and decreasing the intensity of two stationary light sources may cause shifts of the isophotes, and thus provide information about the shape of the object. However, the change of the shadows may be most clearly visible, more than the deforming shading pattern as a whole.

The advantage of the implementation of simulated shadow parallax for laparoscopy over viewpoint parallax or actual shadow parallax is its technical simplicity. While viewpoint parallax and shadow parallax both require moving parts within the laparoscope, simulating shadow parallax can be implemented without any moving parts. Instead, only two separate light guides are needed within the laparoscope. Similar to the horizontal camera movements, simulated shadow parallax was implemented so that one light guide illuminates the observed object from the left, and the other illuminates the object from the right.

Shadow parallax, as it creates shifting shadows, is best applied to situations in which ambiguities are resolved with shifting (cast) shadows. Such an application is industrial endoscopy (Fig. 5.3). Endoscopes, which are called borescopes when used industrially, are used for the inspection of gas turbines generally and aeroplane engines in particular. Borescopes have the advantage that the engine only has to be dismantled for repair, but not for inspection. This reduces expenses (dismantling and reassembling an engine costs about a quarter of a million dollars) and the risk of incorrect reassembling. The size and location of a crack determine whether the engine needs to be repaired. For example, at the end of turbine blades large parts are allowed to be missing while at the root of a blade every crack is the cause of engine repair. Large missing parts at the end of a blade can easily be seen but small cracks at the root are more difficult to observe. If the presence of a crack on a blade is ambiguous the inspectors will compare it with examples of old blades with cracks. Mistakes occur when, for example, a harmless drop of oil is mistaken for a dangerous crack, or even worse, when a dangerous crack is mistaken for a harmless drop of oil. Cracks can be distinguished from a drop of oil by their level relative to the surface. A drop of oil is always on the surface whereas a crack always lies within the surface. Information about height relative to the surface may increase the accuracy of the inspection. For this the inspector may be provided with visual information or cues about relative depth.

Shadow movement parallax may be applicable to industrial endoscopy to make cracks more easily distinguishable. Light source movements generate shifting shadows. The direction and velocity of these shifts potentially indicate the difference between something upon the surface and something within the surface. For example, when the light source moves to the left, oil or dust upon the surface will create a shadow expanding to the right. The expansion

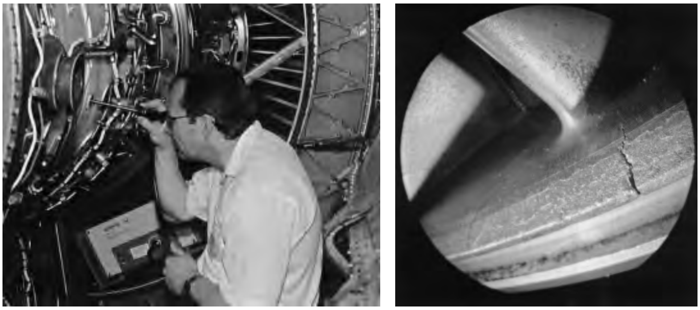

Figure 5.3
An inspector performing a borescope inspection (left) and an example of a crack (right).
[reprinted with permission].

is limited by the height of the object casting the shadow and the amount of movement of the light source. A crack within the surface will include the shaded part, and the expansion is limited by the width of the crack. The information provided by shadow parallax can be used to perform the industrial inspection task more accurately.

In conclusion, in this chapter three experiments are described investigating if shifts generated by a moving light source, or by simulating a moving light source, are sufficient for these types of inspection task.

5.2 Light source vs. camera movements (Exp. 2)

In Exp. 1 (Ch. 4) the feasibility of viewpoint parallax is investigated. In Exp. 2 shadow parallax is compared with viewpoint parallax. In the case of shadow parallax the point of illumination (the light source) is linked with the head movements of the subject. In the case of viewpoint parallax the point of observation (the camera) is linked with the head movements of the subject. Four conditions are compared (Fig. 5.4 gives an overview of the experimental set-up and the conditions):

- Cond. 1: the subject has combined control over the light source and the camera.
- Cond. 2: the subject has control over the light source only.
- Cond. 3: the subject has control over the camera only.
- Cond. 4: the subject has no control.

5.2.1 Method and materials

5.2.1.1 Task and Stimuli

Distinguishing a drop of oil or dust from a crack is basically the same as distinguishing something on the surface from something beneath the surface. A

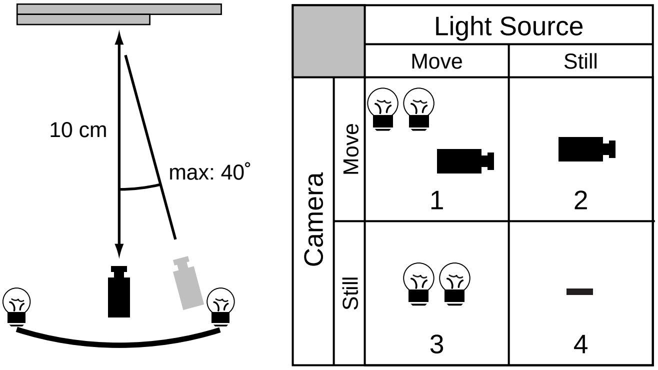

Figure 5.4
An overview of the experimental set-up (left), and an overview of the experimental conditions (right).

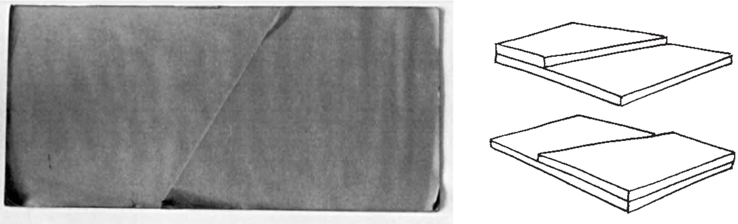

Figure 5.5
An example of a stimulus used during the experiment (left) and how the stimulus was built (right). During the experiment only the centre of the stimulus was shown.

similar problem is created when a piece of paper partly covers a second piece of paper. It is difficult to indicate which of the two sides is on top of the other when shown to a subject who looks with one eye and cannot move the camera. Fig. 5.5 shows one of the fourteen stimuli used. The size of the stimuli (9.5x21 cm) was such that during movement of the camera the border would not be visible to the observer.

Since a crack will rarely be viewed perfectly vertical, the transition in the stimulus has an angle of 30˚ or -30˚ with respect to the vertical. For both angles there were seven height differences. Either the left side could be higher than the right side, or the right side could be higher than the left side, or both sides could be equally high. The differences in height were (from left to right): -3, -2, -1, 0, 1, 2 and 3 times the thickness of the paper (approximate 0.2 mm, grey 80 gsm, N 6.75).

Subjects were asked to indicate as accurately and as quickly as possible which side was on top. There were three choices, for each of which there was a button: the left button had to be selected when the left side was on top, the middle button when both sides were on equal height, and the right button when the right side was on top.

During borescope inspection the degree of confidence is important. If a possible crack is noticed on the monitor, the inspectors verify it by looking directly into the borescope to make sure it is a crack (Ch. 7). Therefore, during the experiment subjects had to indicate the degree of confidence. After selecting a button the subjects were asked to indicate how much confidence they had in the given answer by selecting a number between one and five. One stood for a pure guess and five stood for a hundred percent confidence.

5.2.1.2 Hypotheses

Performance is measured by the amount of time used, the number of stimuli correctly solved and the amount of reported confidence. No difference in performance is expected between viewpoint parallax and shadow parallax. Thus, H_0: $\mu_{vp} \neq \mu_{sp}$; H_1: $\mu_{vp} = \mu_{sp}$ and H_0: $\tau_{vp} \neq \tau_{sp}$; H_1: $\tau_{vp} = \tau_{sp}$, and H_0: $z_{vp} \neq \mu_{sp}$; H_1:

$z_{vp}=z_{sp}$, where μ stands for the mean number correctly solved stimuli, τ stands for the mean amount of time used, z stands for the mean confidence, and subscripts vp to sp stand for viewpoint parallax and shadow parallax.

Comparing the four conditions, it is expected that the active conditions (Conditions 1, 2, and 3 in Fig. 5.4), when the subjects are allowed to explore, will result in better performance compared to the passive condition (Cond. 4), when observers have no control. Thus, H_0: $\mu_{1,2,3} \leq \mu_4$; H_1: $\mu_{1,2,3} > \mu_4$, and H_0: $\tau_{1,2,3} \leq \tau_4$, H_1: $\tau_{1,2,3} > \tau_4$, and H_0: $z_{1,2,3} \leq \mu_4$; H_1: $z_{1,2,3} > z_4$, where μ stands for the mean number of correctly solved stimuli, t stands for the mean amount of time used, z stands for the mean confidence, and subscripts 1 to 4 are the condition numbers.

Comparing the active conditions, Cond. 1 is expected to have the least performance since when camera and light source are both moving the visibility of the behaviour of shadows will be reduced compared to when either the light source or the camera is moving. Thus, H_0: $\mu_1 \geq \mu_{2,3}$; H_1: $\mu_1 < \mu_{2,3}$, and H_0: $\tau_1 \geq \tau_{2,3}$; H_1: $\tau_1 < \tau_{2,3}$, and H_0: $z_1 \geq z_{2,3}$; H_1: $z_1 < {}_{2,3}$. As is argued in the introduction, no difference is expected between Cond. 2, when only the light source is moving, and Cond. 3, when only the camera is moving. and H_0: μ_2, $\neq \mu_3$; H_1: $\mu_2 = \mu_3$, and H_0: $t_2 \neq t_3$; H_1: $t_2 = t_3$, and H_0: $z_2 \neq z_3$; H_1: $z_2 = z_3$.

5.2.1.3 Independent and dependent variables

The experiment had four conditions. All conditions were performed by all subjects. There are 4!=24 ways in which to order the conditions, and an equal amount of subjects participated in the experiment, each performing the conditions in one of the orders. During each condition the subject had to judge all 14 stimuli, which were presented in random order.

The subjects were students from the Faculty of Industrial Design Engineering. They were paid for participating and the experiment took about half an hour for each subject.

5.2.1.4 Procedure

At the start of the experiment an example of a stimulus was shown, and the task was explained. Each of the four conditions was preceded by a training session during which the subjects were allowed to practise the current condition. They were given feedback. During the training session the subjects had to judge a minimum of three stimuli. The training session ended when subjects correctly solved two stimuli in succession.

Each trial started by turning on the light sources, which made the stimulus visible to the subject. Time measurement started simultaneously. Subjects had to decide within ten seconds, since during industrial inspection the turbine blades are also observed only briefly. After 7 seconds a sound indicated that the ten seconds had almost passed. If the subject failed to give an answer in time, neither time nor answer was registered. The moment a button was pressed, or after ten seconds had passed, time measurement stopped and the screen went blank. Between two trials the subjects had time to report their degree of confidence by selecting on a piece of paper a number between 1 and 5.

5.2.1.5 Apparatus

Two light sources were used (Olympus CLK-4, 150W, see Fig. 5.6-right), each located at one side of a small camera (ELMO EM-102 PAL). The distances between the light sources were such that both the camera could freely move in between them, and the light sources could move around the camera (Fig. 5.4). The ratio between the motions of the light source and the head movements of the subjects was equal to the ratio between the motions of the camera and the head movements of the subjects, namely 1:1. Thus, the angle of the subject relative to the monitor is equal to the angle of the camera relative to the stimulus, or light source relative to the stimulus. The image was presented on a colour monitor (20” Trinitron).

Viewpoint movement parallax was implemented using the mechanism shown in Fig. 5.6-left. The camera could make a circular movement around the fixation point in the horizontal plane only. The results of the experiment described in Chapter 4 showed that the movement of subjects concentrated on the horizontal plane. A motor drove the camera movements. The fixation point was located in line with the rotation axis of the motor. The distance between camera and fixation point was approximately 10 cm.

Shadow parallax was implemented using two laparoscopic light sources (Olympus CLK-4, Fig. 5.6-right). These light sources had a mechanical dimmer, which ensured that the colour of the light remains the same when the intensity varies. A motor drives the shaft that controls the light intensity.

The head movements of the subjects were tracked, similar to Exp. 1, using a helmet and encoders. The subjects wore a helmet which was connected by means of a telescopic rod to a rotation axis on top of the monitor which drove the master encoder (500 steps/rotation). When wearing the helmet, the sub-

Figure 5.6
Mechanism for moving the camera (left) and a light source (right).

jects could move freely in all directions. Between rotation axis and the encoder was a transmission of 1:2.5 which made it possible to measure head displacements with an angular resolution of 0.288°/step. Each of the motors used had a slave encoder. A computer controller card (Ratio:ER) was used to relate the measured head movements to the movements of the motor. For each motor a separate control card was used.

5.2.2 Results

Means and 95%-confidence intervals are shown in Fig. 5.7. An ANOVA was performed (Table 5.1 for main and interaction effects). A main effect was found for control over the camera and control over the light source. As expected, both types of control resulted in higher percentage of correct choices compared to no control (Cond. 4). An interaction effect was found for control over the camera and control over the light source. While no differences were expected between the active conditions, combined control (Cond. 1) resulted in a higher percentage correct compared to no control (Cond. 4), but in a lower percentage correct compared to controlling either the light source (Cond. 2) or the camera (Cond. 3). Evidently, combined control over camera and light source provided less information compared to either control over the camera or control over the light source.

For the amount of time used a main effect was found for control over the camera, while no effects were expected. Subjects used more time when they had control over the camera and they could select a point of observation.

For the degree of confidence a main effect was found for the light source. The largest degree of confidence was indicated for controlling the light source (Cond. 2). No difference in degree of confidence was found between combined control over the camera and light source as compared to no control. An interaction effect was found for control over the camera and for control over the light source.

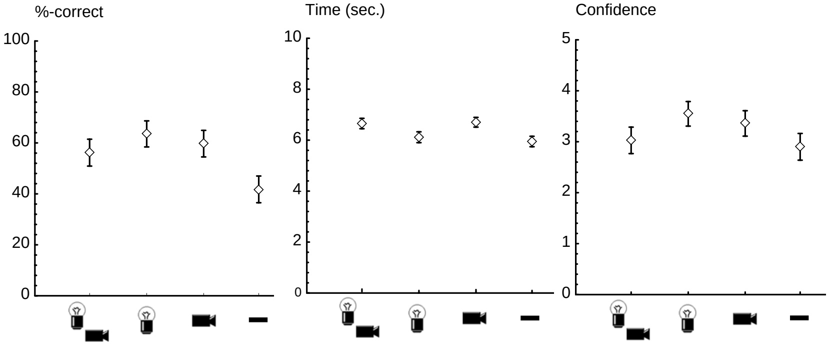

Figure 5.7
Results of Exp. 2 (means and 95% confidence intervals).

Table 5.1: *Overview of the results of the ANOVA .*

Interaction	*F*	*p*
On percentage correct		
Light source	F(1,1312)=9.777	<0.01
Camera	F(1,1312)=4.674	<0.05
Light source x Camera	F(3,1312)=14.567	<0.001
On amount of time used		
Camera	F(1,1312)=49.815	<0.001
On amount of confidence		
Light source	F(1,1312)=4.204	<0.05
Light source x Camera	F(3,1312)=57.982	<0.001

Overall, subjects show the best performance when they have control over the light source (Cond. 2). In that case they have the largest number correctly solved, use the least amount of time and report the highest degree of confidence. This can be explained by the information that can be picked up through exploration compared to what information is required to perform the task. Controlling the light source creates shifting shadows within a stationary image. All shifts indicate which side is on top. Controlling the camera creates parallax shifts. Thus, the inspected surface shows a velocity gradient. Now, the differences in velocity indicate which side is on top because the highest side has large velocity compared to the lower side. Subjects perform Conditions 2 and 3 equally well, but they use more time performing Cond. 3 (controlling the camera only). Subjects show the least performance for Cond. 4, when they have no control. Interestingly, the reported degree of confidence reflects performance. The subjects are evidently well aware of their own performance.

5.3 Simulating a moving light source (Exp. 3)

The experiment described in the previous paragraph (Exp. 2) showed the feasibility of shadow parallax for borescope inspection. However, like a moving camera, a moving light source also requires moving parts within the borescope. If possible there should be no moving parts since the space needed for these movements requires either an increase in outer diameter, a reduction in the amount of illumination, or a reduction in the resolution of the image. As discussed in the introduction of this chapter, shadow parallax can be simulated using two stationary light sources of which the intensity balance varies. The distance between these stationary light sources is expected to be of importance for the effect. For example, if the distance between the light sources is small relative to the distance towards the working area, changes in shading will be less visible compared to when the distance between the light sources is large. Therefore, the effect of the distance between the light sources on the performance of subjects was investigated in an experiment.

5.3.1 Method and materials

Exp. 3 consisted of three conditions, during each of which a different distance between the light sources and the camera was used. Fig. 5.8 gives an overview of the experimental set-up and the three conditions.

5.3.1.1 Task and Stimuli

The task and stimuli used during Exp. 3 were the same as those of Exp. 2. The subjects were asked to indicate as accurately and as quickly as possible which of the two sides was on top. They also had to report their degree of confidence in the answer given.

5.3.1.2 Hypotheses

Again, performance is measured by the amount of time used, the number of stimuli that were correctly solved and degree of confidence. Performance was expected to decrease with decreasing distance between the two stationary light sources, since the visibility of the shadow changes depends on the angle of illumination. Thus, H_0: $\mu_1 \le \mu_2$; H_1: $\mu_1 > \mu_2$, and H_0: $\mu_2 \le \mu_3$; H_1: $\mu_2 > \mu_3$, and H_0: $\tau_1 \le \tau_2$; H_1: $\tau_1 > \tau_2$, and H_0: $\tau_2 \le \tau_3$; H_1: $\tau_2 > \tau_3$ and H_0: $z_1 \le z_2$; H_1: $z_1 > z_2$, and H_0: $z_2 \le z_3$; H_1: $z_2 > z_3$, where μ stands for the mean number of correctly solved stimuli, t stands for the mean amount of time used, z stands for the mean confidence, and subscripts 1 to 3 are the condition numbers.

5.3.1.3 Independent and dependent variables

Exp. 3 consisted of three conditions. There are 3! = 6 orders in which the conditions can be tested. Six subjects participated in the experiment. During each condition the subject had to judge all 14 stimuli. The stimuli were presented in random order. As in Exp. 2, the answer given by the subjects, the amount of time used and the reported degree of confidence were registered.

The subjects were students from the Faculty of Industrial Design Engineering. They were paid for participating. The experiment took about half a hour.

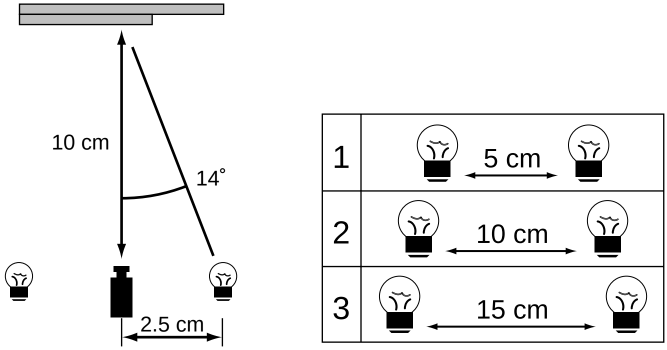

Figure 5.8
An overview of the experimental set-up of Exp. 3 (left) and an overview of the experimental conditions (right).

5.3.1.4 Procedure

The procedure of Exp. 3 was similar to the procedure of Exp. 2, the only difference being that Exp. 2 consisted of four rounds and Exp. 3 consisted of three rounds. Again each round was preceded by a training session during which the subjects were allowed to practise the conditions and during which they were given feedback. During the training session the subjects had to judge a minimum of three stimuli. The training session ended when subjects correctly solved two stimuli in succession.

As in Exp. 2, each trial started by turning on the light sources, which made the stimulus visible to the subject. Time measurement started simultaneously. The moment a button was pressed, or after ten seconds had passed, time measurement stopped and the screen went black. Between two trials the subjects had time to report their degree of confidence by selecting on a piece of paper a number between 1 and 5. Five stood for a hundred percent confidence and one stood for a pure guess.

5.3.1.5 Apparatus

A frame was used in which the camera and light sources were mounted. The experimental set-up is shown schematically in Fig. 5.8. The same light sources were used as in Exp. 2.

5.3.2 Results

Fig. 5.9 shows the results (means and 95%-confidence intervals). The experiment was tested using a t-test. The results show, contrary to what was expected, that performance (number correctly solved) does not increase with increasing distance between light sources and camera. There may be two reasons. First, the stimuli consisted of a sharp edge, providing clear cast shad-

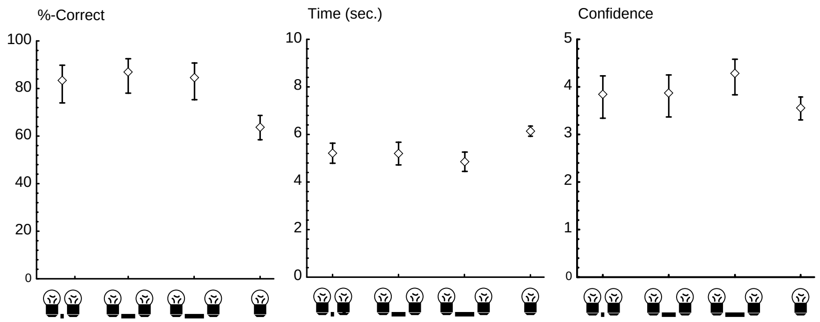

Figure 5.9
The results of Exp. 3. For comparison the results of the second condition of Exp. 2 also are shown.

ows. Subjects only had to look on which side the cast shadow appeared. Second, because the distance towards the stimuli was small relative to the distance between light sources (Fig. 5.8), the cast shadows could be made visible during all conditions. The amount of time used decreases and the degree of confidence increases with the distance between the light sources. When the distance between the light sources is large, i.e. when the cast shadows can easily be made visible, the subjects are faster and more confident compared to Cond. 1, when the distance is smallest.

These results, compared with the result of the second condition of Exp. 2, show an improvement of performance since the 95%-confidence intervals do not overlap. An explanation for this can be found by looking at the difference in the information provided. During Exp. 2, the motions of the light source were linked to the head movements of the subject. The light sources were linked so that the shadows shifted in roughly the same direction to the head movements of the subject, i.e. if the subject moved to the right, both light sources moved to the left. If the left side of the stimulus was the highest, the light source to the left of the camera would increase the amount of shadow cast on the right side of the stimulus. However, the amount of cast shadow would partly be reduced by the light source right to the camera. During Exp. 3 the light sources remained stationary and the intensity of the two light sources was linked to the head movements of the observer. When the observer moved to the right, the intensity of the left light source increased while the intensity of the right light source decreased. Thus, the right light source did not reduce the cast shadows created by the left light source, as it did during Exp. 2, where the intensity of both light sources remained constant.

5.4 Control experiment (Exp. 4)

The results of Exp. 3 show that, for determining the highest side, simulated shadow parallax is feasible. The real life, professional field may differ from the experimental situation in several ways, e.g. the distance from the borescope towards the inspected surface may be larger, and the transition between crack and surface may be more subtle and therefore more difficult to judge. For this reason a fourth experiment was conducted during which the distance towards the stimulus was increased, and where new stimuli were used having a more subtle transition compared to the stimuli used earlier.

5.4.1 Method and materials

Exp. 4 consisted of three conditions, during each of which a different distance between the light sources and the camera was used. Also, the distance from the camera to the stimuli was enlarged to 30 cm (in Exp. 3 it had been 10 cm). Fig. 5.10 gives an overview of the experimental set-up and the three conditions.

5.4.1.1 Task and stimuli

The bases of the stimuli used were similar to those of the stimuli previously used. They were made out of two pieces of cardboard, one partly covering the other. However, they differed from the previous stimuli in that each was covered with a piece of felt. This made the transition smoother and it was therefore more difficult to judge which was the higher side. Fig. 5.11 shows a stimulus. During the experiment only the centre area of this stimulus was visible on the monitor. The colour of the felt used approximated the colour of the stimuli used in the first experiment (N 6.75).

The task in Exp. 4 was equal to that in Exp. 3. Again, the subjects were asked to indicate as accurately and quickly as possible which of the two sides was on top. They also had to report their degree of confidence in the given answer.

Six subjects participated in the experiment, who were paid for participating.

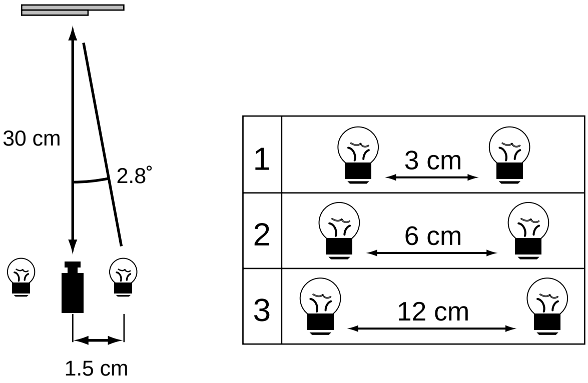

Figure 5.10
overview of the experimental set-up of Exp. 4.

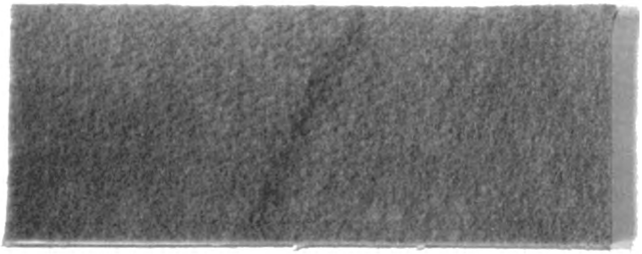

Figure 5.11
Example of a stimulus used in Exp. 4. During the experiment only the centre of the stimulus was visible.

5.4.1.2 Hypotheses

As in the previous experiments, performance is measured by the amount of time used, the number of stimuli correctly solved and the degree of confidence. The hypotheses are the same as the hypotheses of the second experiment described in this chapter.

5.4.2 Results

Means and 95%-confidence intervals are shown in Fig. 5.12. Exp. 4 was evaluated using a t-test. For the number correctly solved a difference was found between Cond. 1 and 2 (p<0.01) and between Conds 1 and 3 (p<0.001). No difference was found between Conds 2 and 3. Similar results were found for the amount of time used. For the amount of time used Cond. 1 was found to differ from Cond. 2 (p<0.001) and from Cond. 3 (p<0.001) but no difference was found between Conds 2 and 3. For the degree of confidence Cond. 1 was found to differ from Cond. 2 (p<0.001) and from Cond. 3 (p<0.001) but no difference was found between Conds 2 and 3. These results correspond to the expected results. The amount of information obtained through movement increased with the distance between the light sources and the camera. As in

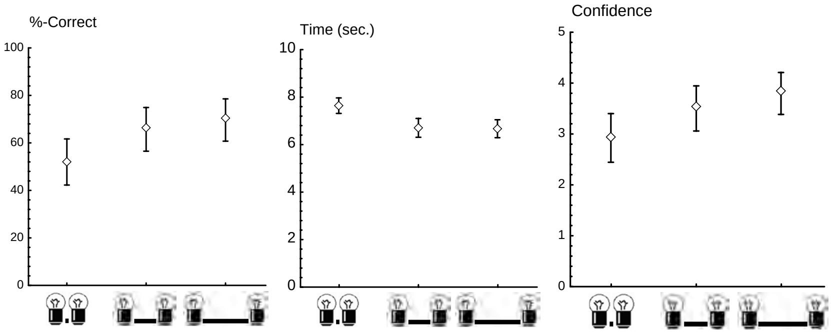

Figure 5.12
results of the third experiment. Means with 95%-confidence intervals.

Exp. 3, the stimuli used were not difficult enough to show a difference in performance between Conds 2 and 3.

5.5 Discussion and conclusions

In Exp. 2 the feasibility of controlling the motions of the light source or the motions of the camera was investigated. It was found for determining the highest side that either controlling the light source or controlling the camera is applicable.

Controlling both camera and light source in the same way is not advisable since a light source coherently moving with the camera reduces the amount of visible shadow changes. This suggests that the light source and the camera should move independently. This is not possible with current borescopes and laparoscopes, since the light source and camera are integrated into one device and thus only coupled control is possible. Independent control requires an additional light source. For example, for industrial use an additional light source can be entered into the engine through a different bore-hole. For medical use, an additional light source can be entered into the abdomen through a different trocar (i.e. the device through which the instruments enter the abdomen, see Chapter 1). Schurr *et al.* [1996] describe a trocar which has an integrated light source. This trocar was not proposed as an independent light source, instead it was proposed to provide background lighting in addition to the light source built into the laparoscope. The trocar could be used as an independent light source, for example, when used for the insertion of instruments. However, this would have the disadvantage that the light source is then linked to the movements of an instrument.

In Exp. 3 the feasibility of simulating shadow parallax with two stationary light sources of which the intensity balance varies was investigated. Results indicate that for detecting differences in height, simulated shadow parallax is feasible. The distance between the light sources was found to influence the amount of time used and the degree of reported confidence, but not the performance. An influence on performance was expected since a larger distance between light sources allows the visibility of larger differences in shadows.

Therefore, in Exp. 4 the distance between the light sources was reduced compared to this distance in Exp. 3, and new stimuli were used with less apparent shadows. For these new stimuli the distance between the light sources was found to influence performance. For a small distance between the light sources it was difficult to perceive whether the left or the right light source was casting the shadow. Thus, the distance between the light sources should be as large as possible.

Technical limitations may restrict the distance between the light sources, e.g. when there is no room to place the light sources far apart. Restrictions on the distance between the light sources occur when shadow parallax is used for medical applications, but not when it is used for industrial applications. Medically used endoscopes, laparoscopes, are direct-viewing, i.e. the viewing direction is in line with the laparoscope. The distance between the light sources is then restricted by the diameter of the laparoscope. Industrially used endoscopes, borescopes, are side-viewing, i.e. the viewing direction is perpendicular to the borescope. For side-viewing borescopes the distance between the light sources is less restricted since the distance is constraint only by the length of the borescope which enters the area that is inspected.

In conclusion, shadow parallax was found to be applicable for observation tasks such as occur during industrial use. In medical use, however, observation aids manipulation. The applicability of shadow parallax for manipulation tasks, such as occur during medical use, will be discussed in the next chapter.

The next chapter will also discuss the possible advantage of combining viewpoint parallax and shadow parallax. Exp. 2 showed that it is best if the light source and the camera move independently. This suggests that there is an advantage in using shadow parallax to simulate a stationary light source rather than moving the camera. For example, when the laparoscope moves to the right, a light source movement to the left can be simulated by increasing the intensity of the left light source while decreasing the intensity of the right light source.

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[1] Although shadows are the most ‘pregnant’ visual cues, the entire shading of the scene also is influenced when moving the light source.

CHAPTER 6

CREATING SHIFTS

Viewpoint and shadow parallax combined

This chapter is an adapted version of:

Voorhorst, F.A., Meijer, D.W., Overbeeke, C.J., & Smets, G.J.F.
Depth perception in Laparoscopy through perception-action coupling.
Minimally invasive therapy, & Allied technologies. [1998, accepted]

6.0 Introduction

In the previous chapters two types of control actions (Ch. 2) were investigated: changing the point of observation (viewpoint parallax, Ch. 4), the feasibility of which was investigated for an observation and a manipulation task, and changing the point of illumination (shadow parallax, Ch. 5) the feasibility of which was investigated only for an observation task. Viewpoint parallax has the advantage that it allows the surgeon to select a new point of observation but it has the disadvantage that it requires a complex mechanism inside the laparoscope. Shadow parallax does not allow the surgeon to select a new point of observation, but it has the advantage of simple implementation because a moving light source can be simulated by two stationary light sources the intensity balance of which varies (Ch. 5). Implementation does not then require moving parts within the laparoscope, but only requires two separate light guides. Both principles were shown to be feasible for observation tasks (Chs 4 and 5). Two questions remain in order to determine which principle to implement.

The first question that remains is how shadow parallax compares to movement parallax. During laparoscopic operation, observation tasks support manipulation tasks. Viewpoint parallax was investigated in combination with a manipulation task (Ch. 4), shadow parallax was not. It was found that, contrary to observation tasks, manipulation tasks do not invite head movements. Instead, subjects tend to sit as still as possible. Reduced head movements may be caused by the manipulation task being straightforward, and therefore do not invite subjects to make head movements. For example, the manipulation task during Exp. 1, described in Chapter 4, consisted of positioning the instrument, as subjects were asked to touch a point with the tip of the instrument.

To perform this task successfully subjects only had to monitor the distance between the tip of the instrument and the point to be touched. If this distance can be monitored from their current point of observation, subjects will not select a new point of observation and thus will not move. The set-up of the experiment was indeed such that this distance could be monitored without selecting a new point of observation. However, during laparoscopic operation the shortest distance between the tip of the instrument and the tissue may not be visible at all times, and it can be expected that surgeons will make head movements.

Reduced head movements during manipulation may also be caused by the instrument used. For example, an instrument may be difficult to control because it requires manual steadiness, e.g. the instrument used in Exp. 1 (Ch. 4). In that case the instrument constrains the freedom of making head movements. The extent to which an instrument constrains head movements depends on the experience of the operator with the instrument. Cole *et al.* [1991, Merrit *et al.* 1991] found large differences in performance between non-experienced and experienced subjects, and suggested that the complexity of controlling the instrument may interfere with head movements.

The second question that remains is whether the laparoscope should be held by the assistant or by a mechanical support. During all previous described experiments, the mechanism to move either the camera or the light source was held by a mechanical support. Such mechanisms could be used during these experiments because the location of the area of interest remained stationary, and the direction of the camera therefore did not have to be changed. During laparoscopic surgery, however, the location of the area of interest, i.e. the location of the instruments, does change. The advantage of an assistant holding the laparoscope is that an assistant not only holds the laparoscope but also keeps it directed towards the area of interest when its location changes. The disadvantage, however, is that the assistant makes small movements with the

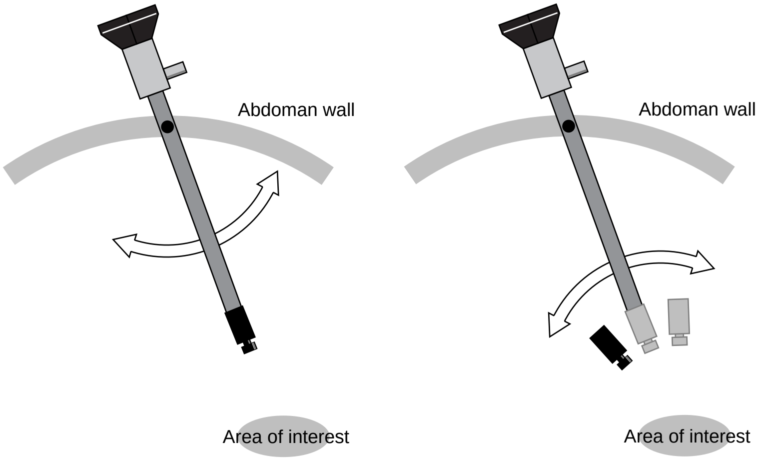

Figure 6.1
The movements of the laparoscope are generated by the assistant (left), who is holding the laparoscope, may interfere with the explorative movements of the surgeon (right).

laparoscope. As mentioned in Chapter 4, these movements differ from the explorative movements around a fixation point generated by the surgeon. The motions of the laparoscope caused by the assistant and the movements of the tip of the laparoscope generated by the surgeon may conflict (Fig. 6.1).

An alternative for the laparoscope being held by an assistant is the laparoscope mounted in a mechanical support. The advantage of a mechanical support is that, during exploration, all movements of the laparoscope are controlled by the surgeon. The disadvantage, however, is that a mechanical support may have to be readjusted when the location of the area of interest changes. Therefore, a robotic support is frequently suggested as an alternative to the assistant directing the laparoscope. The surgeon, who has control over the robot, additionally performs the task of the assistant: i.e. to keep the laparoscope directed at the working area. The surgeon can be provided with control over the robot in a number of different ways. For example, the movements of the laparoscope can be linked with the head movements of the surgeon [Finlay *et al.* 1995]. They make use of a magnetic tracker to measure the head position of the surgeon, and when a pedal is pressed, the robot is linked up with the head movements of the surgeon. The laparoscope can also be controlled using only a pedal [Gracia *et al.* 1996, Sackier et al .1994], or it can be controlled by voice control [Geis *et al.* 1996], by means of a large joystick [Hurteau *et al.* 1994, Begin *et al.* 1995], or by means of a small joystick which can be attached to one of the surgeon's instruments [Taylor *et al.* 1995]. These solutions provide the surgeon with the ability to select a fixation point. In Exp. 1 the advantage of the ability to explore was shown for the situation where the area of interest was already selected. To allow the surgeon control over the selection of the area of interest a robotic support could be used in combination with a DVWS-based laparoscope. Whether or not the assistant has to direct the laparoscope, or whether a mechanical (or robotic) support is needed, depends on whether the motions introduced by the assistant hinder the surgeon.

Two experiments will be described in this chapter. In the first experiment (Exp. 5) viewpoint parallax and shadow parallax are compared. In the second experiment (Exp. 6) the influence of the motions generated by the assistant on the performance of the surgeon is investigated.

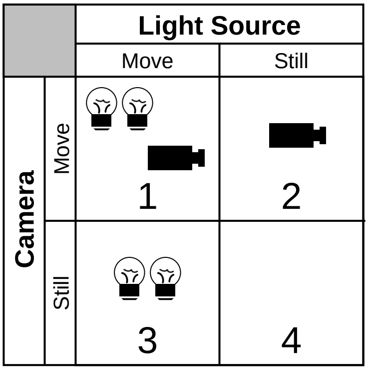

Figure 6.2
Experimental set-up of the first experiment showing the four conditions (1: shadow parallax and viewpoint parallax combined, 2: viewpoint parallax, 3: shadow parallax, 4: no control).

6.1 Shadow vs. viewpoint parallax (Exp. 5)

6.1.1 Method and materials

In Exp. 5 four different conditions were compared (Fig. 6.2):

- Cond. 1: the subject is assisted by both viewpoint parallax and shadow parallax.
- Cond. 2: the subject is assisted by viewpoint parallax only.
- Cond. 3: the subject is assisted by shadow parallax only.
- Cond. 4: the subject has no control over his visual information.

6.1.1.1 Apparatus

The apparatus (mechanism for light sources and head tracking device) used for this experiment and the mechanism for moving the camera were similar to those described in Chapter 5. The camera could make a circular movement around the fixation point in the horizontal plane only. The fixation point was located in line with the rotation axis of the motor, which drove the camera movements. The distance between camera and fixation point was approximate 6 cm.

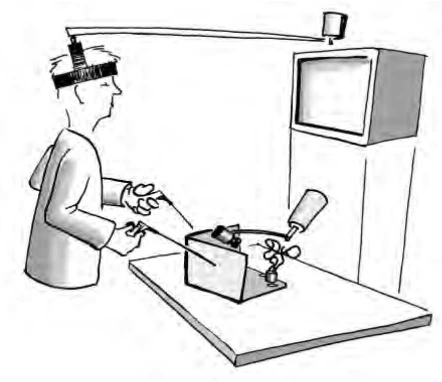

Figure 6.3
An overview of the set-up with a subject wearing the helmet which is connected with an encoder on top of the monitor. The encoder and the motor driving the camera are linked.

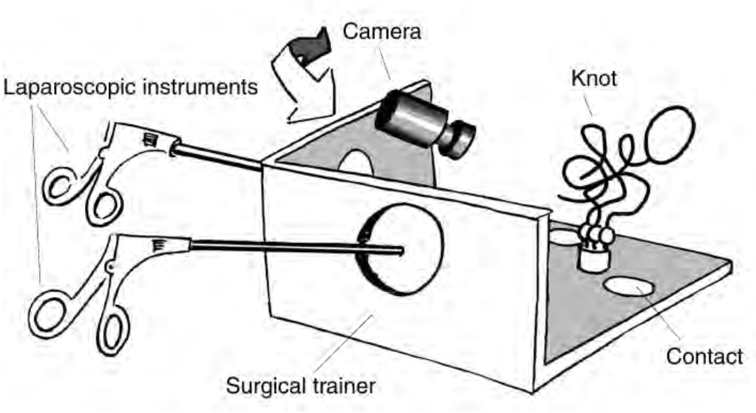

Figure 6.4 *Overview of the experimental set-up. Note the contacts on both sides of the knot. The right contact is touched at the beginning of a trial, the left contact is touched at the end.*

Shadow parallax was implemented using two laparoscopic light sources (Olympus CLK-4). The light sources were identical to the ones used during Exps 2 to 4, as described in Chapter 5. The rotation axis, with which the intensity could be varied, was again linked to the rotation axis of a motor. The intensity balance of both light sources could be regulated.

The intensity of the stationary light sources and the movements of the camera were linked with the head movements of the subjects. The subjects wore a helmet connected to the rotation axis of an encoder (the master encoder) by means of a telescopic rod. While wearing the helmet, the subjects could move freely in all directions. The master encoder, located on top of the monitor, measured the movements of the subjects relative to the monitor in the horizontal direction. The movements of the motor were linked to the head movements of the subjects by using a computer controller card. For each motor a separate control card was used.

Fig. 6.3 gives an overview of the set-up with a subject wearing the helmet. The distance towards the monitor was approximately 80 cm. For the experiment a laparoscopic simulator was used (Fig. 6.4). The simulator was basically an open box made out of wood with the top and two sides removed. The two remaining sides had a circular opening filled with a piece of rubber. The instruments entered the surgical trainer through a small hole in the rubber. During the experiments two conventional laparoscopic instruments were used. The subjects were seated and could not see directly into the surgical trainer.

6.1.1.2 Task and stimuli

The stimuli used were knots made out of three wires (Fig. 6.5). The root of each wire was labelled with a small coloured sphere. One of the wires terminated with a loop. The knot was placed inside the laparoscopic simulator. On

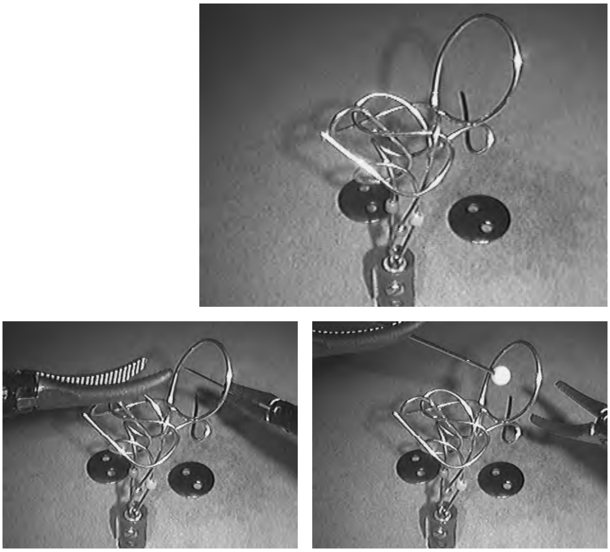

Figure 6.5
An example of a stimulus used during the experiment (ltop. It is a knot made out of three wires. Each of the wires is labelled with a colour. In the background two electrical contacts are visible. The left contact had to be touched at the beginning and the right contact at the end of each trial. The bottom pictures show the manipulation task.

the right side of the knot on the floor of the simulator there was a start contact. On the left side there was a stop contact (schematically shown in Fig. 6.4, and also visible in Fig. 6.5).

The subjects were asked to perform two tasks: an observation and a manipulation task. The subjects started with the observation task and were asked to determine the colour label of the wire with which the loop was connected. The observation task started by turning on the illumination inside the surgical trainer. Time measurement started simultaneously. Subjects gave their answers orally. These were registered by the experimenter who then pressed the corresponding button. Time measurement stopped when the button was pressed. The subjects were asked to perform the observation task as fast as possible.

The subjects then had to perform a manipulation task. The subjects were asked to manoeuvre a needle through the loop of the knot (Fig. 6.5). Before the manipulation task really started, the subjects had to pick up a needle and were given time to adjust the orientation of the needle relative to the manipulator and the layout of the knot. After they indicated they were ready the experimenter gave a start signal. The subjects started by touching the “start” contact. A sound signal indicated that it was touched. After the needle was manoeuvred through the loop the “stop” contact had to be touched. Touching this contact made the screen go blank and stopped the time measurement and the registration of the number of times the knot was touched. The subjects were asked to perform the manipulation task without touching the knot with the needle.

6.1.1.3 Dependent and independent variables

Eight subjects, who all worked at the Academic Medical Centre (AMC) of Amsterdam (Amsterdam University hospital), participated in the experiment. The subjects were either experienced surgeons or were trainee surgeons with experience of laparoscopic surgery (approximately 30 operations). The amount of time used was recorded as well as the number of times the knot was touched with the needle.

6.1.1.4 Hypotheses

First, the active conditions (Conds 1 to 3) vs. the passive condition (Cond. 4) are considered. During the active conditions the observer will be able to obtain spatial information, and therefore it is expected that performance is better in both the exploration and the manipulation task as compared to the passive condition. The null hypotheses and the alternative hypotheses are $H_0{:}\mu_a \leq \mu_p$, $H_1{:}\mu_a > \mu_p$, and $H_0{:}\tau_a \leq \tau_p$, $H_1{:}\tau_a > \tau_p$ where μ stands for the mean number of correctly solved puzzles, τ stands for the mean time used and subscript a and p stand for the active and passive conditions.

Secondly, shadow parallax (Cond. 3) vs. viewpoint parallax (Cond. 2) is studied. Because the task to be solved is a spatial puzzle, it is expected that viewpoint parallax will result in better performance since viewpoint parallax allows the subjects to observe the knot from different orientations and obtain more spatial information as compared to shadow parallax. The null hypotheses and the alternative hypotheses are $H_0{:}\mu_v > \mu_s$, $H_1{:}\mu_v \leq \mu_s$, and $H_0{:}\tau_v > \tau_s$, $H_1{:}\tau_v \leq \tau_s$ where μ stands for the mean number of correctly solved puzzles, τ stands for the mean time used and subscript v and s stand for viewpoint parallax respectively shadow parallax.

Thirdly, a combination of shadow parallax and viewpoint parallax (Cond. 1) is compared to either one of them (Conds 2 and 3). Because shadow parallax simulates the light source moving independently of the camera, it is expected that a combination of shadow parallax and viewpoint parallax will lead to better performance as compared to either shadow parallax or viewpoint parallax. The null hypotheses and the alternative hypotheses are $H_0{:}\ \mu_{vs} > \mu_v$, $H_1{:}\ \mu_{vs} \leq \mu_v$, $H_0{:}\ \tau_{vs} > \tau_v$, $H_1{:}\ \tau_{vs} \leq \tau_v$, and $H_0{:}\ \mu_{vs} > \mu_s$, $H_1{:}\ \mu_{vs} \leq \mu_s$, $H_0{:}\ \tau_{vs} > \tau_s$, $H_1{:}\ \tau_{vs} \leq \tau_s$ where μ stands for the mean number of correctly solved puzzles, τ stands for the mean time used, subscript vs, s and v stand for a combination of shadow parallax and viewpoint parallax and subscript s and v stand for shadow parallax and viewpoint parallax.

6.1.1.5 Procedure

After an explanation of both the experimental set-up and the task had been given by the experimenter, the subjects performed a training session. Subjects were allowed to start with the experiment after twelve rounds of practice. During the experiment twelve knots were presented in random order. On each of these knots both tasks had to be performed. The training session and the experiment together took about 45 minutes.

6.1.2 Results

6.1.2.1 Observation task

The results were evaluated using an 8 (subjects) X 2 (viewpoint parallax) X 2 (shadow parallax) ANOVA. For the percentage correct, only a main effect was found for viewpoint parallax (F(1,48) = 5.786, p<0.05). No second-order effect was found, nor were differences found in the amount of time used. Fig. 6.6 shows the mean number of correctly solved knots with 95% confidence intervals. Cond. 4 (no control) was found to differ from Cond. 1 (t-test, p<0.001) and Cond. 2 (t-test, p<0.05), Cond. 3 was not found to differ from Conds 2 and 4, but was found to differ from Cond. 1 (t-test, p<0.01). Fig. 6.6 clearly suggest the advantage of viewpoint parallax and shadow parallax (Con. 1) However, no difference was found between Conds 1 and 2 nor between Conds 3 and 4. Thus, for this task, only viewpoint parallax was found to improve performance.

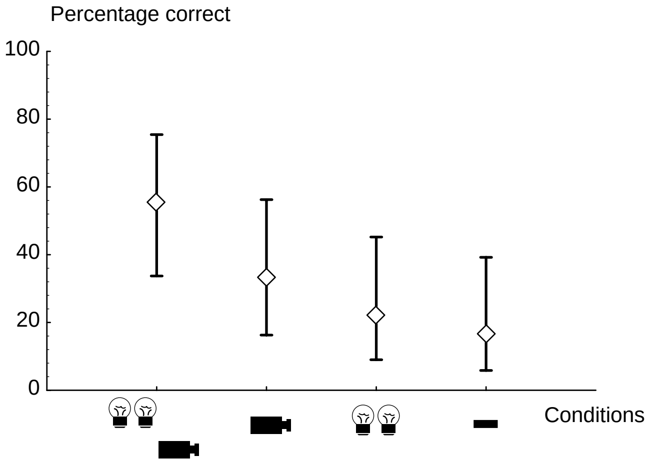

Figure 6.6
The number of times a knot was correctly solved (percentage correct) during the observation task of Exp. 5 (means and 95% confidence intervals, N = 8).

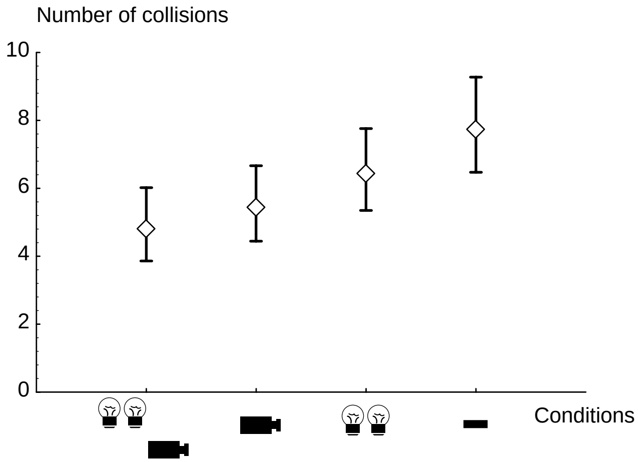

Figure 6.7
The number of times a knot was touched (collisions) during the manipulation task of Exp. 5 (Means and 95% confidence intervals, N = 8).

6.1.2.2 Manipulation task

The results were tested with an ANOVA. During three trials subjects lost the needle. These trials were excluded from analysis. Having control over the movements of the camera was found to be an advantage for this manipulation task as a main effect was found for viewpoint parallax (F(1,45) = 5.166, $p<0.05$). A combination of viewpoint parallax and shadow parallax was not found to be an advantage, as no second order effect was found, nor was an effect found for the amount of time used. Fig. 6.7 shows means and 95% confidence intervals of the number of times the knot was touched during the manipulation task. Cond. 4 was found to differ from Cond. 1 (t-test, $p<0.001$) and Cond. 2 (t-test, $p<0.01$). Cond. 3 was found to differ from Cond. 1 (t-test, $p<0.05$) but not from Conds 2 and 4. Again, Fig. 6.7 suggests the advantage of a combination of viewpoint parallax and shadow parallax (Con. 1). However, no difference found between Conds 1 and 2 nor between Conds 3 and 4. Nor were any time differences found. Thus, for this manipulation task, only viewpoint parallax was found to improve performance.

6.2 The influence of the assistant (Exp. 6)

This experiment compared four different conditions (Fig. 6.8):

Cond. 1: the observer controls both viewpoint parallax and shadow parallax while the laparoscope is directed by an assistant.

Cond. 2: the observer controls both viewpoint parallax and shadow parallax while the laparoscope is mechanically supported.

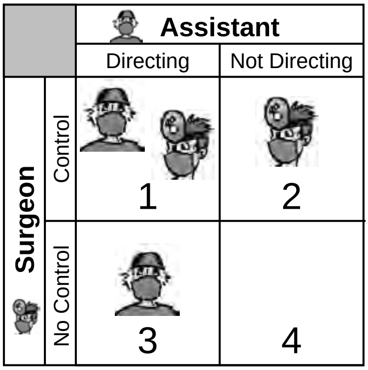

Figure 6.8
The experimental set-up of the second experiment showing the four conditions (1: the surgeon controls the movements of the tip while the laparoscope is held by an assistant, 2: the surgeon controls the movements of the tip while the laparoscope is mounted in a mechanical support, 3: the surgeon has no control while the laparoscope is held by an assistant, 4: the surgeon has no control while the laparoscope is mounted in a mechanical support).

Cond. 3: the observer has no control over his visual information while the laparoscope is directed by the assistant.

Cond. 4: the observer has no control over his visual information while the laparoscope is mechanically supported.

6.2.1 Method and materials

The apparatus and the technical set-up were similar to those of the first experiment. The task, stimuli, procedure and measured variables were the same as in Exp. 5.

6.2.1.1 Hypotheses

First, the active condition vs. the passive condition was considered. Again, as in Exp. 5, the active condition is expected to result in better performance as compared to the passive condition for both tasks. The null-hypotheses and the alternative hypotheses are $H_1{:}\mu_a < \mu_p$ $H_0{:}\mu_a \geq \mu_p$, and $H_1{:}\tau_a < \tau_p$ $H_0{:}\tau_a \geq \tau_p$ where μ stands for the mean number of correctly solved puzzles, τ stands for the mean time used and subscript a and p stand for the active and the passive conditions.

Second, the human assistant vs. the mechanical support was considered. The condition during which the laparoscope is mechanically supported is expected to result in better performance compared to the condition in which it is supported by the assistant, since the motions of the assistant conflict with the explorative movements of the subject. The null hypotheses and the alternative hypotheses are $H_0{:}\mu_m < \mu_h$ $H_1{:}\mu_m \geq \mu_h$, and $H_0{:}\tau_m < \tau_h$ $H_1{:}\tau_m \geq \tau_h$ where μ stands for the mean number of correctly solved puzzles, τ stands for the mean time used and subscript m and h stand for mechanical and human support.

Third, a combination of control and mechanical support was studied. It is expected that whether the subject has control over his visual information is more important than how the laparoscope is supported. The null hypotheses and the alternative hypotheses are H_0: $\mu_a < \mu_p$, H_1: $\mu_a \geq \mu_p$, H_0: $\tau_a < \tau_p$, H_1: $\tau_a \geq \tau_p$, and H_0: $\mu_m > \mu_h$, H_1: $\mu_m \leq \mu_h$, H_0: $\tau_m > \tau_h$, H_1: $\tau_m \leq \tau_h$, where μ stands for the mean number of correctly solved puzzles, τ stands for the mean time used and subscript a, p and m, h stand for the active and passive condition and mechanical and human support.

6.2.2 Results

6.2.2.1 Observation task

The results were evaluated with an ANOVA. For the percentage correct a main effect was found for combined control over viewpoint parallax and shadow parallax (F(1,32) = 5.818, $p<0.05$). No second-order effect was found, nor was an effect found for the amount of time used.

Fig. 6.9 shows means and 95% confidence intervals of the number of times the knot was correctly solved during the observation task. Cond. 4 was found to differ from Cond. 1 (t-test, $p<0.001$), Cond. 2 (t-test, $p<0.001$), and Cond. 3 (t-test, $p<0.01$). No significant difference was found between Conds 1, 2 and 3. Thus, when the surgeon has the ability to explore, or when the assistant provides movements of the laparoscope, his performance of an observation task increases whereas the amount of time used remains the same.

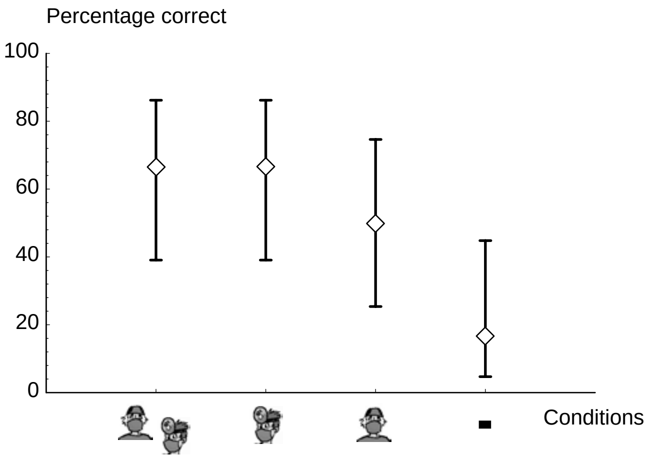

Figure 6.9

The number of times a knot was correctly solved (percentage correct) during the observation task of Exp. 6 (means and 95% confidence intervals, N = 6).

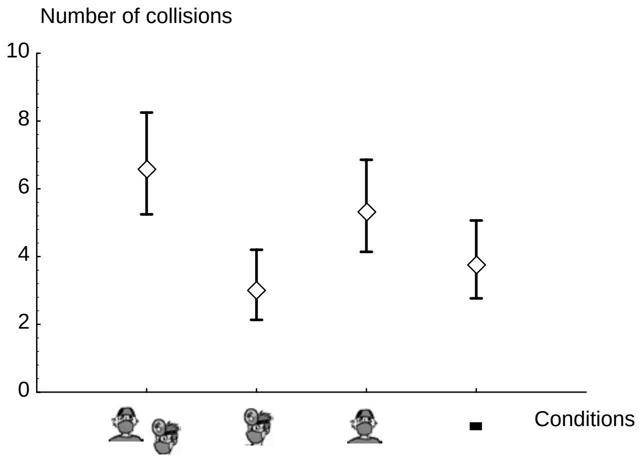

Figure 6.10
Number of times the knot was touched (collisions) during the manipulation task of Exp. 6 (means and 95% confidence intervals, N = 6).

6.2.2.2 Manipulation task

The results were evaluated with an ANOVA. During one trial a subject lost the needle; this trial was excluded from the analysis. For the number of collisions a main effect was found for the assistant (F(1,31) = 6.478, $p<0.05$). No second-order effect was found, nor was an effect found for the amount of time used. Fig. 6.10 shows means and 95% confidence intervals of the number of collisions during the manipulation task. Cond. 4 was found to differ from Cond. 1 (t-test, $p<0.001$) and Cond. 3 (t-test, $t<0.01$), but not from Cond. 2. No difference was found between Conds 2 and 4, nor between Conds 1 and 3.

While the assistant was not found to have an effect on the performance of the observation task, he was found to have an effect on the performance of the manipulation task (Cond. 2 was performed better than Conds 1 and 3). The reason for this may be that for the observation task either the movements generated by the surgeon or the movements generated by the assistant make the spatial structure of the knot perceivable. Thus, the motions of the laparoscope generated by the assistant do not interfere with the explorative movements of the surgeon. However, during the manipulation task the motions generated by the assistant do interfere with the explorative movements of the surgeon as they alter the point of observation and make it more difficult for the surgeon to determine in which direction to move the needle (Ch. 3).

6.3 Discussion and conclusions

The results of the observation task of Exp. 5 show that viewpoint parallax improves performance compared to the passive condition. Performance is not found to improve for shadow parallax. Evidently, for these stimuli and this environment, simulated shadow parallax alone does not provide enough information to perform this task. Similar results are found for the manipulation task. The number of collisions reduces when the surgeon is assisted by viewpoint parallax, allowing him to select an optimal point of observation.

A combination of viewpoint parallax and simulated shadow parallax is not found to improve performance compared to viewpoint parallax alone. In Exp. 5, viewpoint parallax and shadow parallax are combined so that a stationary light source is simulated relative to a moving camera (Cond. 1 in Fig. 6.2). A previous experiment had shown that the light source and the camera have to move independently (Exp. 2, in Ch. 5), and therefore it was expected that combining viewpoint parallax and shadow parallax would be an advantage. However, while the results do show a trend which suggests that a combination of viewpoint parallax and shadow parallax can be an advantage, they argue in favour of viewpoint parallax unsupported by shadow parallax (similar to Cond. 2). This may be due to the task and the stimuli used since the advantage of shadows with respect to this task and these types of stimuli is small which, for example, may not be true for more organically shaped surfaces.

The results of Exp. 6 show that the assistant has no effect on the performance of the observation task. Performance is found to depend on viewpoint parallax. For the manipulation task the results reversed. Viewpoint parallax does not influence the number of collisions during the manipulation task. Instead, the assistant is found to increase the number of collisions. This indicates that the movements generated when the assistant directs the laparoscope hinder the surgeon performing a manipulation task. Not only is this found for the situation in which the surgeon has no control over the movements of the laparoscope (Cond. 3), but also for the situation in which the surgeon has partial control (Cond. 1). These results argue in favour of a mechanical support to provide the surgeon with sole control over the movements of the laparoscope.

The results of the manipulation part of both experiments show a difference when comparing the active and the passive condition. Conds 1 and 4 of Exp. 5 correspond to Conds 2 and 4 of Exp. 6. Whereas a difference between the active and passive condition is found in Exp. 5, it is not found in Exp. 6. There may be two explanations. First, since the manipulation task is more difficult to perform when the assistant supports the laparoscope, the subjects may be tempted to manipulate more carefully. Second, the subjects participating in Exp. 6 had already participated in Exp. 5 and therefore may have been more experienced. Cole *et al.* [1991] found a large difference in performance between experienced and non-experienced operators. This would suggest that the manipulation task was not difficult enough for an experienced operator to benefit from controlling his visual information.

It is often suggested that stereoscopic information is required to perform a spatial manipulation task [Merrit *et al.* 1991, Cole *et al.* 1991, Spain *et al.* 1991]. Because manipulation tasks invite subjects to sit as still as possible, spatial perception based on perception-action coupling would be best applied only to the observation tasks [e.g. Cole *et al.* 1993]. This was also the conclusion from the results of a previous experiment (Ch. 4). The results of the experiments described in this chapter show that perception-action coupling applied to a manipulation task also improves performance. Evidently it is not only the task to be performed which invites subjects to sit as still as possible. this also is invited by the instruments used. For example, in Exp. 1 (Ch. 4) a manipulator was used, for which the subjects needed extensive practice. The difficulty in operating the instrument made subects sit as still as possible. This was also found by Merrit *et al.* [1991], who used a large rod for manipulation, and Spain *et al.* [1991], who used a robotic manipulation arm. These manipulators are larger than the laparoscopic instruments, and need more concentration to manipulate them. Accordingly, they impose more restrictions on movements. In Exps 5 and 6 conventional laparoscopic instruments were used, and the subjects were experienced with these instruments. This, and the fact that these instruments are light, may have positively influenced the subjects' ability to move and explore during manipulation.

In conclusion, the surgeon should be provided with control over the movements of the laparoscope when performing an observation task. When performing a manipulation task the laparoscope should not be directed by the assistant.

The results strongly suggest the advantage of a combination of viewpoint parallax and shadow parallax over viewpoint parallax alone. This corresponds with previously found results (Exp. 2), which showed that the camera and the light source should move independently. However, the advantage of this combination was not found to be significant. Therefore, for these types of tasks, implementation would be best focussed on viewpoint parallax alone.

The Chapters 4, 5 and 6 have described experiments investigating what visual information the surgeon should have control over. The next chapter will discuss possible technical implementations investigating how the surgeon can be provided with control over his visual information.

CHAPTER 7

IMPLEMENTATION

Coupling perception and action

7.0 Introduction

The experiments described in the previous chapters investigated how perception-action coupling has to be implemented to improve the performance of the tasks occurring during laparoscopic operation: observation and manipulation tasks. As this thesis is concentrating on implementation, these experiments were conducted in close relation with implementation.

Until now, in this thesis theoretical considerations and experiments have been discussed. Chapter 2 has discussed information in the context of the interaction between a user and his environment. Chapter 3 has, from a theoretical viewpoint, zoomed in on the information needed by the surgeon during laparoscopy. What information is needed was explored in the experiments described (Chs 4, 5 and 6). The results of these experiments consider one side of implementation, namely feasibility with respect to the user. They indicate what information is needed with respect to the task to be performed. For example, Exp. 1 (Ch. 4) showed the feasibility of viewpoint parallax for observation tasks, i.e. the performance of subjects improved when they were provided with control over their point of observation, but not for manipulation tasks. Apart from feasibility from a perceptual point of view, technical realisation has to be considered as well.

Technical realisation has been explored in close relation with the experiments investigating feasibility. The results of one experiment initiated new technical realisations which, in turn, initiated new questions to be tested in new experiments. Therefore, similarities between the content of the previous chapters and the implementations described in this chapter are not accidental.

This chapter is divided into five sections. In the first section a recapitulation is given of how affordances were made operational (Ch. 2), and what perceptual information is required for observation and manipulation tasks (Ch. 3). These will condense into three criteria for implementation. In the second section a description is given of the exploration of technical realisations for providing the surgeon with control over his visual information. In the third section a description is given of the technical realisation that has been completed in a working prototype. The fourth section gives a description of the evaluation of this prototype in a practical setting. The chapter ends with a discussion of the design process.

7.1 Criteria for implementation

As described in Chapter 2, designing for interaction has to consider two aspects: what is controlled ("controlled actions") and how it is controlled ("control actions"). In Chapter 3 it was argued that the surgeon should be provided with control over his visual information. The control action is the movement of the surgeon's head. Technically this can be realised with, for example, an infra-red detection device which measures the position of a small reflector, or with a specially designed stool that measures the slant of the upper body.

Two controlled actions were tested for their feasibility, namely viewpoint parallax, i.e. the observer has control over the point of observation (Chs 4 and 6), and shadow parallax, i.e. the observer has control over the point of illumination (Chs 5 and 6). Both types of controlled actions were tested for two types of tasks: observation tasks (Chs 4, 5 and 6) and manipulation tasks (Chs 4 and 6). Based on theoretical considerations it was hypothesised that observation tasks require the spatial layout to be specified relative to the point of observation (Ch. 3). It was found that the performance of an observation task improves when a subject has control over either the point of observation or the point of illumination (Exps 1 to 6). On theoretical considerations it was hypothesised that manipulation tasks, apart from a specification of the spatial layout relative to the point of observation, also require the point of observation to be specified relative to the viewpoint of the observer (Ch. 3). It was found that the performance of a manipulation task improves when the surgeon has control over the movements of the laparoscope, i.e. when the point of observation is related to his viewpoint (Exps 1, 5 and 6).

The main difficulty when implementing the DVWS for laparoscopy is the technical realisation. Preferably, the mechanism for moving the camera should be as simple as possible. However, the mechanism is bound to be complex because the fixation point, around which the camera has to move in a circular manner, is located in front of the tip of the laparoscope (Fig. 7.1-right),

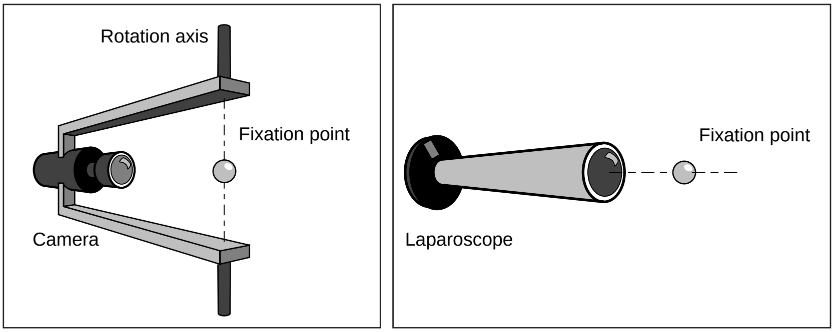

Figure 7.1
A mechanism which includes the fixation point (left). Such implementation is not possible for laparoscopy because the fixation point is located in front of the laparoscope (right).

which makes a simple solution, such as that shown in Fig. 7.1-left, impossible. Instead, the mechanism for rotating the camera around the fixation point has to be included within the laparoscope, and therefore will be complex.

Possible implementations are constrained in three ways. First, there are perceptual constraints, i.e. what information has to be provided for the task to be performed. These are approximately indicated by the results of the experiments described in the previous chapters. Second, there are medical constraints, i.e. the instruments cannot be allowed to harm the patient. For example, instruments must not lose parts, since these can be overlooked and left behind inside the patient without being missed. Also, any part of the instrument that can make contact with either the surgeon, the patient, or another instrument that makes contact with either one of them, must be capable of being sterilised. Other parts of the instrument must be clean, but they do not have to be sterile. Third, there are constraints with respect to usability, i.e. the

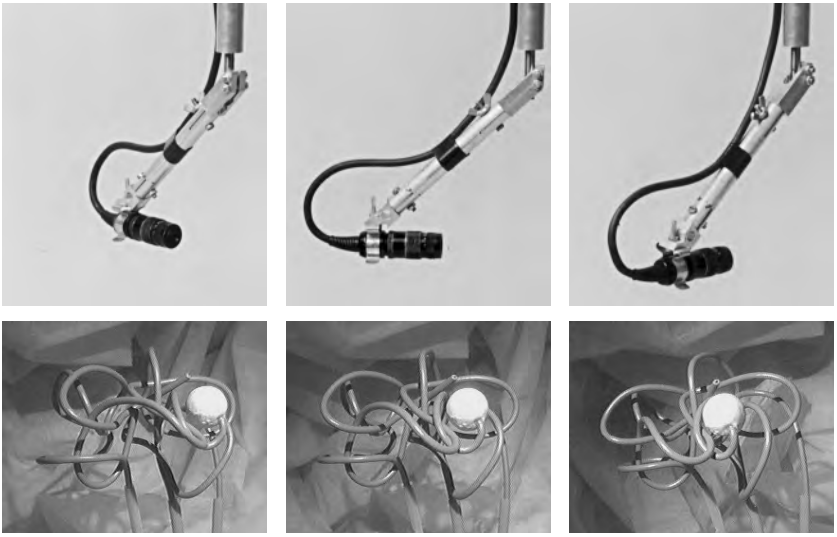

Figure 7.2
A mechanism which has the fixation point included (top), and a set of images obtained when moving the camera around an object, in this case a knot made out of three wires, one of which terminates in a white sphere (bottom).

surgeon must be able to use the implementation to obtain the required information. This is not as trivial as it seems. For example, manipulation tasks that require manual steadiness invite the surgeon to stand as still as possible. Linking the motions of the laparoscope to the movements of the surgeon to provide for spatial information during such tasks may be feasible in theory, but in practice it is not. Thus the implementation has to be such that the surgeon can use it within the constraints of laparoscopic operation.

In conclusion, a DVWS based laparoscope has to fulfil the following three requirements:

- It has to provide the information needed to perform the task. Observation tasks either need viewpoint parallax (Chs 4 and 6) or shadow parallax (Ch. 5), and manipulation tasks should have no uncontrolled motions of the laparoscope (Ch. 6).
- It must not harm the patient, so it has to be sterilisable, which means that at least those parts have to be sterile which make contact with either the surgeon, or the patient, or with an instrument that makes contact with either one of them. Furthermore, it must not break up into fragments, otherwise parts may be left behind inside the body of the patient.
- It has to be usable, i.e. its controlled actions and its control actions must be made perceivable both by the spectator and by the user (Ch. 2). For example, the surgeon should be able to explore the working area, which means that the surgeon must perceive how to direct it, or to readjust the distance towards the fixation point. This also includes, for example, that it must be small enough to be inserted.

The first criterion was investigated in Chapters 4, 5 and 6. The second criterion provides for technical restrictions on implementation, such as choice of materials used and the ability to be dismantled. The last criterion is the most difficult one, as this has to do with usability. These two last criteria will be the focus of attention in this chapter.

7.2 Exploring the technical possibilities

7.2.1 Moving a camera inside the laparoscope

From the results of Exp. 1 (Ch. 4), investigating the feasibility of viewpoint parallax, the following was concluded:

- The performance of an observation task improves when the observer is allowed to explore (viewpoint parallax). Initially this was not found to be true for manipulation tasks (Exp. 1, Ch. 4), but later experiments (Exps 5 and 6, Ch. 6) indicated the importance of manual steadiness that is required for manipulation.

- The movements during exploration are small, when a distinction is made between movements to select an angle of observation and movements to explore this relative to this angle of observation (Exp. 1).

This indicates the feasibility of a laparoscope which has a built-in moving camera. To demonstrate the DVWS on a small scale, a mechanism was designed and built inside a tube with an inner diameter of 30 mm [Prototype 1, Subroto, 1991]. Instead of a camera, a small glass fibrescope was used. The tip of the fibrescope could move in the horizontal plane, around a fixation point. Movements in other directions were not implemented. The fixation point was located at a distance of 30 cm in front of the prototype and the maximum angle of rotation relative to this point was approximately 20°. Fig. 7.3 shows the prototype.

Fig. 7.4-left gives a schematic overview of the mechanism. Fig. 7.4-right gives the orientation of the tip of the fibrescope (schematically shown by a camera) for different positions. It shows that the movements of the tip of the fibrescope approximate a circle, but that it does not always aim at the fixation point. The deviation from the fixation point is not noticed during usage. What can be noticed, however, is the non-linearity between the movements of the observer and the motions of the camera. The ratio of the angle of rotation of the disc and the angle of observation of the camera (Fig. 7.5) increases for large angles of observation, which results in an acceleration of camera motions for constant head movements. People who tried this prototype only noticed this acceleration when it was pointed out to them.

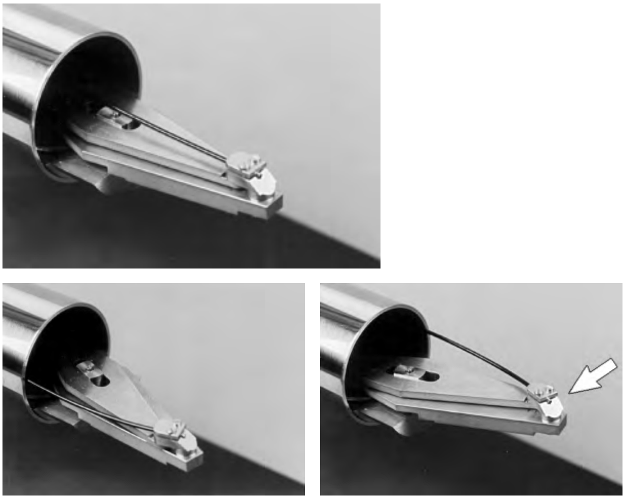

Figure 7.3

Prototype 1: a mechanism with in the tip of the laparoscope for moving a fibrescope (the arrow indicates the tip of the fibrescope).

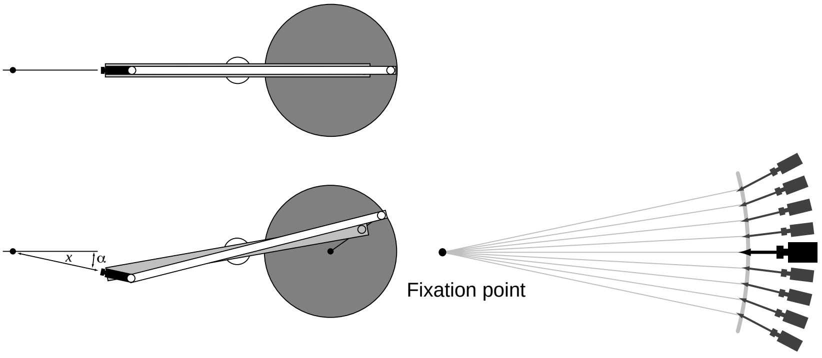

Figure 7.4
Schematic overview of the mechanism producing circular camera movements around a fixation point (left) and the orientation of the camera for different camera positions (right).

Prototype 1 demonstrated the feasibility of viewpoint parallax for a laboratory set-up, i.e. the prototype was fixed in a mechanical support. However, in a more realistic situation, when the laparoscope was not fixed but directed by an assistant or by the surgeon himself, the motions of the camera were found to be too small.

This prototype has three disadvantages. First, it requires a complex mechanism inside the laparoscope and therefore becomes expensive and difficult to sterilise. Second, the mechanism is relatively large because of the space required within the laparoscope to move the camera. Therefore, the size of the parallax shifts is limited. And third, the orientation of the laparoscope does not predict the angle of observation. Because the mechanism is built into the laparoscope, the direction in which the camera is pointed cannot be seen from the outside. Therefore, the observer has to move the laparoscope first before being able to select a new working area.

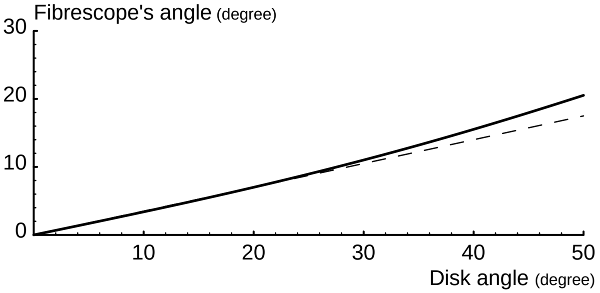

Figure 7.5
Transmission ratio between observation angle and the angle of the fibrescope's tip.

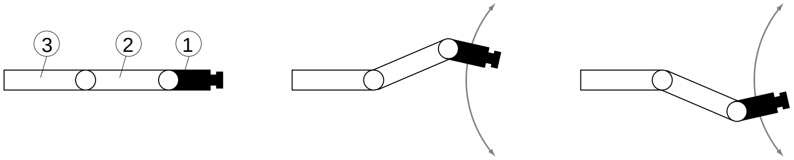

Figure 7.6
Three segments are used to rotate a camera around a fixation point.

7.2.2 Moving the tip of the laparoscope

The main disadvantage of moving a camera within a rigid laparoscope is the limited space available which allows only limited motions of the camera. Outside the laparoscope more space is available, as the abdomen is inflated. Therefore, instead of moving the camera inside a rigid laparoscope, the tip of a non-rigid laparoscope can be made to move. The space available for movements of the tip of the laparoscope inside the abdomen will be larger than the space available for movements of a small camera inside the laparoscope.

Moving the tip can be achieved by dividing the laparoscope into three segments (Fig. 7.6). The camera is located in the first segment. To create camera motions around a fixation point these segments can be controlled individually. For example, two motors can be included within the laparoscope to control the movements of segment one and segment two relative to segment three. However, this increases the weight of the laparoscope. Alternatively, the segments can be controlled using wires. This technique is commonly used to control the tips of flexible endoscopes. The advantage of using wires is that the motors can be located outside the laparoscope. The disadvantage is that it is difficult to keep perfectly stretched wires. If they are not perfectly stretched they introduce dead time, i.e. the motor can rotate over several degrees while the segment which is controlled remains stationary. Preferably the movements of segment one and two are coupled, such that a minimum of motors can be used, and wires of minimal length.

7.2.2.1 Combined control over the segments

Fig. 7.7 shows a mechanism which can be used to control segment one and segment two in combination. It consists of two discs, disc 1 and disc 2, which are connected by means of a rod and a wire. Disc 1 is fixed relative to its own axis. Disc 2 can rotate around its own axis (axis 2), and can also rotate around the axis of disc one (axis 1). If disc 2 rotates clockwise around axis 1, the wire connecting both discs generates a counterclockwise rotation of disc 2 around axis 2. If the diameters of the two discs are equal, angle will be equal to angle. Thus, the rotation around axis 2 will compensate for the rotation around axis 1. If both discs have equal diameter, a camera connected to disc 2 will remain horizontal during rotations of disc 2 around axis 1. If the diameters of the

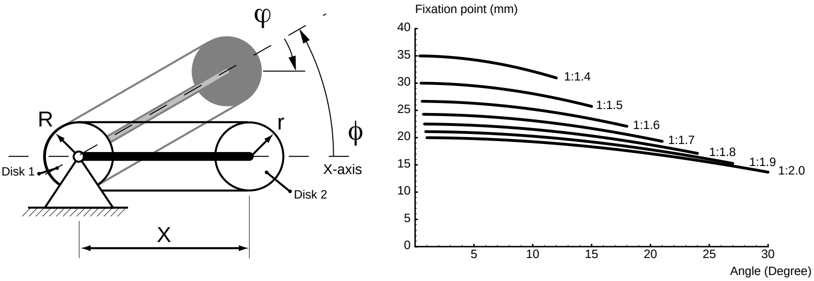

Figure 7.7 *Schematic overview of the mechanism (left) and the distance towards the fixation point as a function of the angle of rotation for different ratios of R and r (right).*

discs are not equal, e.g. if the diameter of disc 2 is smaller than the diameter of disc 1, the rotation around axis 2 will be larger than the rotation around axis 1. In that case the camera will not remain horizontal but will instead point towards the horizontal axis (Figs. 7.6 and 7.7).

The motion of the camera will only approximate a circular movement around the fixation point. The location of the fixation point relative to axis 1 can be determined as follows (Fig. 7.7-left):

When disc 1 has a diameter of 2R and disc 2 has a diameter of 2r, then the amount of rotation of disc 2 around axis 2 in relation to the amount of rotation around axis 1 equals:

$$\varphi = \phi \times \frac{R}{r} \qquad (1)$$

When the distance between disc 1 and disc 2 equals X then the position of disc 2 equals:

$$\begin{aligned} x_2 &= X \times Cos(\phi) \\ y_2 &= X \times Sin(\phi) \end{aligned} \qquad (2)$$

The angle of rotation of disc 2 relative to the horizontal axis is $\varphi - \phi$. The horizontal distance towards the fixation point relative to axis 2 equals:

$$x_f = \frac{y_2}{\sin(\varphi - \phi)} \times \cos(\varphi - \phi) \qquad (3)$$

Combining (1), (2) and (3) results in the distance towards the fixation point relative to axis 1:

$$f_x(\phi) = X \times \left[\cos(\phi) + \frac{\sin(\phi)}{\tan(\phi \times (1 - \frac{R}{r}))}\right] \qquad (4)$$

If the distance between disc 1 and disc 2, X, remains constant, the location of the fixation point depends on the ratio $\frac{R}{r}$. Fig. 7.7-right shows for a number of different ratio’s (1:1,4 to 1:20) the distance towards the fixation point as function of rotation angle ϕ. It shows a decay as ϕ increases. Thus, the distance towards the fixation point becomes smaller.

To demonstrate the principle a prototype (Prototype 2) was built (Fig. 7.8, App. II-A for the technical drawing). This led to a number of observations. First, in order for the surgeon to explore the working area, the entire laparoscope has to be directed towards this working area (i.e. the fixation point has to be located inside the working area). As the distance towards the working area may differ, the distance towards the fixation point is preferably relocatable. Second, the wires connecting the first and second segment may have to be newly strained after some time in use. Third, to facilitate large motions of the camera the second segment should preferably be as long as possible.

7.2.2.2 Reallocating the fixation point

Depending on the distance between the tip of the laparoscope and the working area, the distance towards the fixation point is adjustable. If the working area is close, the distance to the fixation point will have to be shorter compared to when the working area is at far away. The advantage of independently controlling both moving segments is that the location of the fixation point can be altered. Prototype 2, described in the previous section, has a fix-

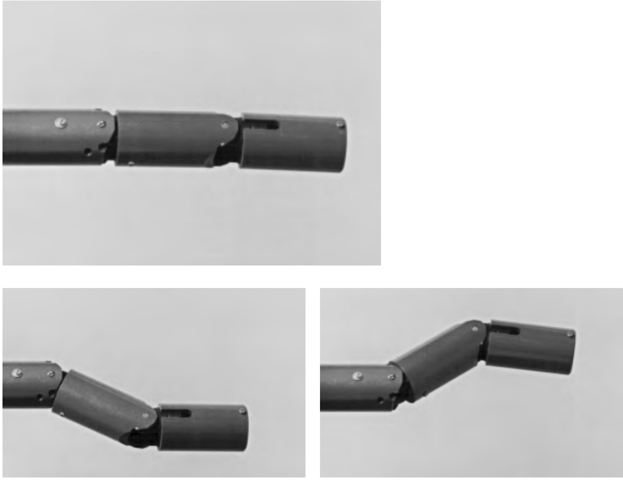

Figure 7.8
Prototype 2: based on the mechanism shown in Fig. 7.6. The prototype has a diameter of 32 mm.

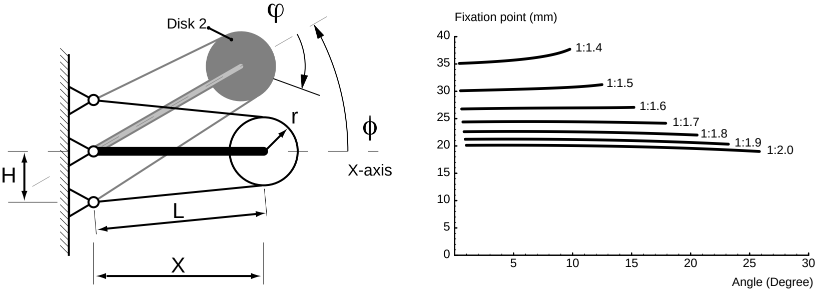

Figure 7.9 *schematic overview of the mechanism (left) and the distance towards the fixation point as function of the angle of rotation for different ratios of H and R (right).*

ation point at a distance depending on the choice of the diameter of disc 1 and the diameter of disc 2. To make the fixation relocatable, only a small adjustment of this mechanism is needed.

The location of the fixation point depends on the diameter of disc 1 relative to the diameter of disc 2 (Fig. 7.7). If disc 1 is replaced by a rod the location of the fixation point depends on the length of the rod. Fig. 7.9 shows the resulting mechanism. The location of the fixation point can be calculated as follows. H is the distance between the rotation point of the bar and the connection point of the wire. When $\phi = 0$ length L is:

$$L_{\phi=0} = \sqrt{(H-r)^2 + (X)^2} \qquad (5)$$

For $\phi \neq 0$ the position where the wire will connect to disc 2 will change as the wire acts as a tangent of the disc. However, this shift will be small, and is therefore discarded to keep the calculation simple. Then length L for $\phi \neq 0$ is:

$$L(\phi) = \sqrt{(H \times \sin(\phi) - r)^2 + (X + H \times \cos(\phi))^2} \qquad (6)$$

The rotation of disc 2 equals the change of length L:

$$\Delta L = L(\phi) - L_{\phi=0} \qquad (7)$$

The angle of rotation then of disc 2 then is:

$$\varphi = \frac{\Delta L}{r} \qquad (8)$$

Fig. 7.9 shows the distance towards the fixation point as function of ϕ for different H. When the ratio is large, and the distance towards the fixation is small

(Fig. 7.9), there is less decay as the ratio increases, indicating that the location of the fixation point is more stable compared to the situation with two discs (Fig. 7.7). However, if the ratio is small and the distance towards the fixation large, Fig. 7.9 is not at all equivalent to Fig. 7.7 (the situation with two discs). Moreover, the situation with a rod and a disc is only feasible for large X, because then the strain of the wires caused by rotating the rod will be compensated by the wire's elasticity.

For changing the location of the fixation point the length H has to be changed or, more precisely, the length of the projection of H on the plane of which axis-2 is the normal has to be changed. This length can easily be changed by rotating the rod around the x-axis (Fig. 7.10). The projection of the rod (H in Fig 7.9) and the projection of the wires are shown in grey.

To demonstrate the principle, the mechanism was implemented in a prototype with a diameter of 20 mm (Prototype 3, Fig. 7.11, App. II-B shows the technical drawings of this prototype). The change in location of the fixation point could be made visible. Prototype 3 was only used to show the possibility of technical implementation, and not to show the feasibility of a camera linked to the head movements.

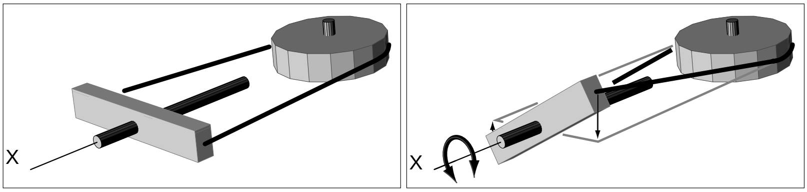

Figure 7.10
Rotating the rod around the x-axis makes the transition and thus the position of the fixation relocatable.

The segmented prototypes described (Prototypes 2 and 3) allow larger motions of the camera compared to a laparoscope with a built-in movable camera (Prototype 1). However, there are four disadvantages. First, they contain a complex mechanism which makes sterilisation difficult. Second, it is difficult to implement light guides for illuminating the area of interest because

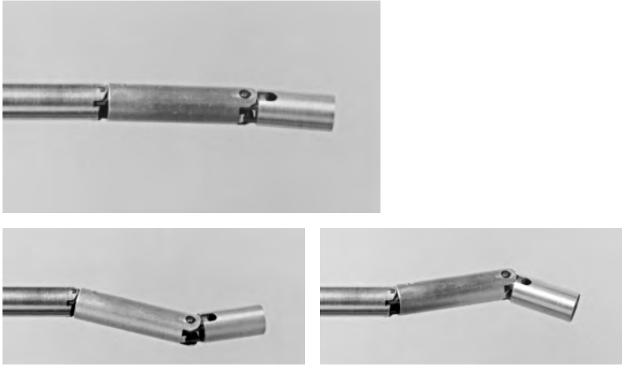

Figure 7.11
Prototype 3: based on the mechanism shown in Fig. 7.8. The prototype has a diameter of 20 mm.

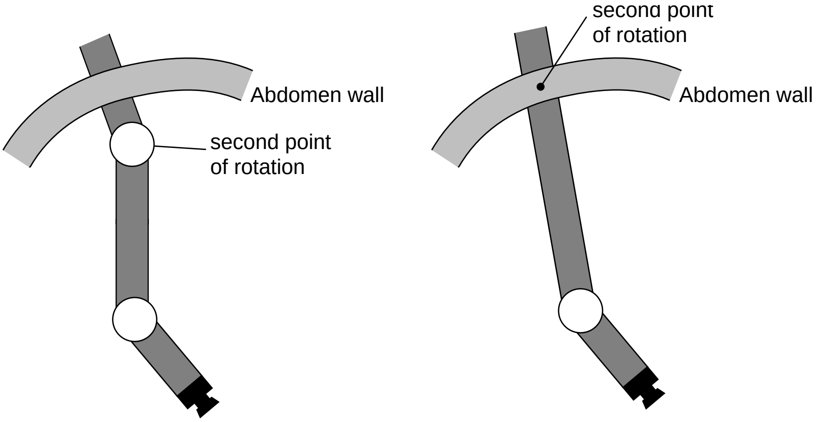

Figure 7.12
If rotation around the abdomen wall is allowed, then the second point of rotation can be omitted.

the amount of space available for the light guides is restricted by the mechanical parts. Third, these prototypes have to be inserted so that at least the first two segments are inside the patient. This disadvantage, however, disappears when the trocar is allowed to rotate around the abdomen wall. The abdomen wall functions as the second rotation point. This is illustrated in Fig. 7.12. The resulting mechanism has only two segments. Rotating the trocar around the abdomen wall and simultaneously controlling the tip of the prototype is technically complex as it requires a mechanism which provides combined control over the rotations of the trocar and the movements of the tip of the prototype. Rotating the trocar only partly solves the problem of minimal insertion, since some degree of insertion is still needed. Also, the laparoscope still has to include a complex mechanism. Fourth, it is impossible to determine the orientation of the tip relative to the laparoscope from the outside of the abdomen. For an assistant, who is holding the laparoscope and cannot perceive the direction of the tip, it is difficult to direct the laparoscope.

7.2.2.3 Adapting the idea of a rolling link

The prototypes presented in the previous section have a mechanism included within the laparoscope by which the segments are linked and movable relative to each other. To sterilise them they either have to be completely sealed, or it must be possible to disassemble them. Rotation axes cause particular difficulties.

A mechanism which does not make use of rotation axes is the so-called rolling-link mechanism [Kuntz, 1995]. This mechanism was designed for its high energy transmission. A rolling link exploits the fact that two elements in pure rolling contact, without slip, have no friction. This fact is used to make links of high mechanical efficiency. Fig. 7.13-left shows a rolling cylinder on a horizontal plane. The only friction absorbing energy may be the friction

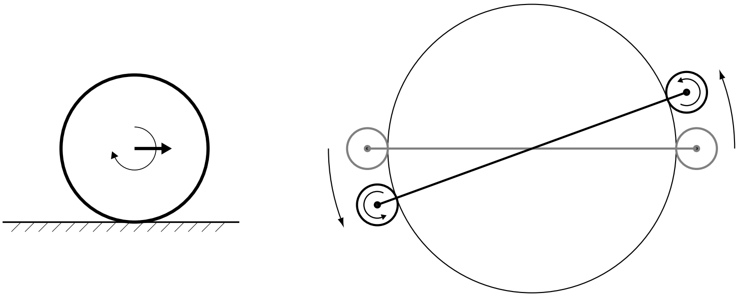

Figure 7.13
A rolling object has minimal resistance (left) and rolling objects implemented for a rolling link mechanism (right).

force at the point where the cylinder makes contact with the surface, combined with microslip. However, elements in pure rolling contact have no slip. The principle of rolling contacts can be used in different configurations, see for example Fig. 7.13-right.

Apart from high mechanical efficiency, rolling links also have the advantage of creating a rolling link without using spindles. The absence of spindles for holding the segments together can be adapted to make the laparoscope easily dismantlable. For example, the mechanism shown in Fig. 7.13-left can be used as basis for a segmented laparoscope. This results in the theoretical solution shown in Fig. 7.14.

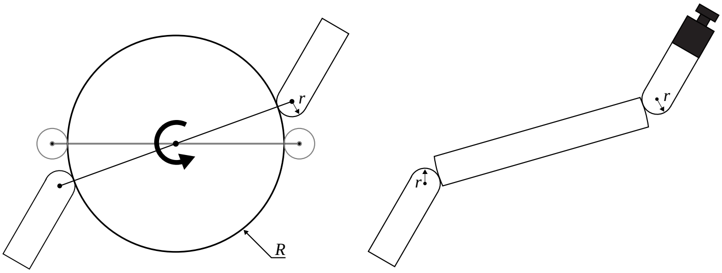

Figure 7.14
the rolling-link principle applied to the segmented laparoscope.

For the mechanism to work, the three segments have to be held together. Kuntz [1995] uses bandages to hold the rollers together. A similar approach can be taken for the laparoscope. The segments can be held together using bands, which are located on the outer side of the laparoscope, connecting the first and the last segment. Removing these bands automatically disconnects the three segments of the laparoscope, which then can be sterilised separately. However, simplifying the dismantling of the laparoscope does not necessarily ensure separate sterilisation. Therefore, to achieve separate sterilisation, the bands can be designed so that they have to be replaced before each operation, for example because the choice of material in combination with the diameter of the bands causes it to stretch after it has been used for a certain

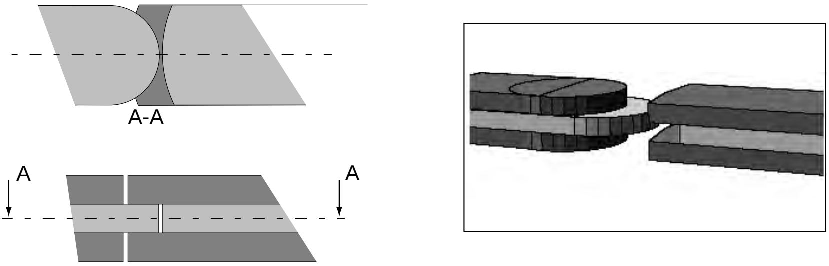

Figure 7.15
Adding supports to absorb perpendicular forces.

period of time. Removing the old bands automatically splits the laparoscope and separate sterilisation is then part of normal routine. The feasibility of this requires that replacing the bands is very simple.

Three difficulties remain. First, a rolling-link mechanism allows for planar movements but a force perpendicular to this plane of movement will not be supported. Supporting these forces and maintaining high energy transmission is difficult. However, since the rolling link is used for its simplicity rather than maximum energy transmission, supports are added to absorb perpendicular forces (Fig. 7.15). Second, the signal wire for the camera has to travel through the laparoscope. The camera is located in the first segment and has to be connected with the monitor outside the abdomen. An opening through which the wire travels through the laparoscope must be sufficiently wide for it to be easily removed and inserted. Third, the light guides for illuminating the working area will be difficult to include. Alternatively, a trocar with integrated light guides can be used for illumination [Schurr *et al.* 1996].

Contrary to segmented prototypes described earlier, the laparoscope based on the rolling-link mechanism (Prototype 4) reveals on the outside of the abdomen how the tip is oriented inside the abdomen. The tip of the laparoscope is controlled by rotating the third segment relative to the second segment (Fig. 7.16). For rotating the third segment relative to the second segment, the third segment and part of the second will have to be on the outside of the abdomen. Since the orientation of the third relative to the second segment corresponds to the orientation of the tip relative to the second segment, the orientation of the third segment shows the orientation of the tip.

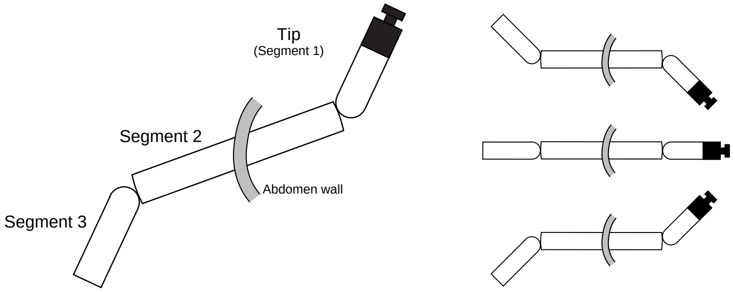

Figure 7.16
Prototype 4: a segmented laparoscope based on a rolling-link mechanism. (left) The orientation of the tip can be seen from outside the abdomen.

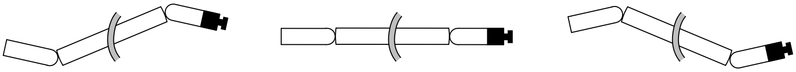

Figure 7.17
Exploring an area of interest by rotating segment 3 relative to segment 2 in combination with rotating segment 2 relative to the point at which it enters the abdomen.

Prototype 4 is not suitable for linking the motions of the camera to the head movements of the surgeon. To explore an area of interest, the third segment has to be rotated around the second segment and the second segment has to be rotated in the opposite direction around the point where it enters the abdomen (Fig. 7.17). Combined control over the third segment and second segment is a possible solution for linking to the head movements of the surgeon, but this requires a complex mechanism. However, instead of linking the camera motions to the head movements of the surgeon, his laparoscope may be suitable for manual control, i.e. the surgeon controls the camera movements by hand, for example, for exploratory laparoscopy. During exploratory laparoscopy no manipulation is performed. Thus, not an assistant but the surgeon will control the laparoscope. For such tasks a mechanical solution based on a rolling link may be feasible. Fig. 7.18 shows Prototype 4, illustrating the concept.

The prototypes (Prototypes 2, 3 and 4) described in this section all have the disadvantage that they involve moving parts which have to be inserted into the patient. They were therefore not developed further. Instead, research has concentrated on the feasibility of a principle which does not require any moving parts to be inserted into the patient, namely shadow parallax (Ch. 5). The next section will describe two prototypes based on shadow parallax.

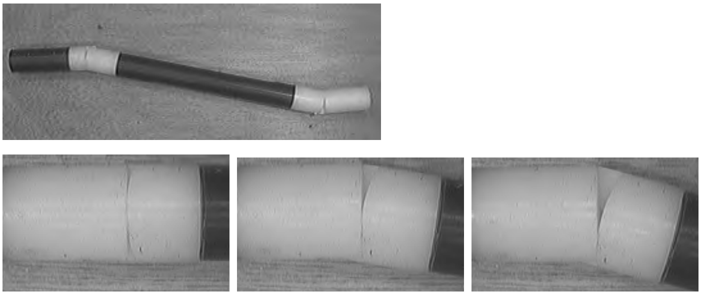

Figure 7.18
First prototype based on the rolling-link mechanism.

7.2.3 Moving the light source

From the results of the experiments investigating the feasibility of shadow parallax (Exps 2, 3 and 4, described in Ch. 5) the following was concluded:

- For observation tasks control over the light source movement (shadow parallax) is feasible (Exp. 2).
- The camera preferably moves independently from the light source (Exp. 2).
- A light source movement can be simulated by two stationary light sources of which the intensities vary (simulated shadow parallax, Exp. 3).
- When simulating shadow parallax the distance between the stationary light sources is preferably as large as possible (Exp. 4).

Technical implementation remains the main stumbling-block for implementing viewpoint parallax for laparoscopy. In Chapter 5 an alternative to viewpoint parallax was described, namely shadow parallax. This has the advantage over viewpoint parallax that it can be simulated with two stationary light sources the intensity of which varies. For simulated shadow parallax no moving parts are needed within the laparoscope. Instead, only two separate light guides are needed, each of which terminates to one side of the image guide. This section will describe two implementations of shadow parallax: one for industrial use, which was designed in co-operation with Tom Djajadiningrat, the other for medical use.

The experiments described in Chapter 5 showed that the distance between the light sources affected performance, and that preferably this distance has to be as large as possible. The distance between the light sources for a direct viewing borescope is restricted by its diameter. However, borescopes used in industry are commonly side-viewing because of which there are less restrictions of the distance between the light sources. This has two advantages. First, the distance between the light sources is not restricted by technical limitations (e.g. size of the borehole), but by user demands. Second, the tip can be

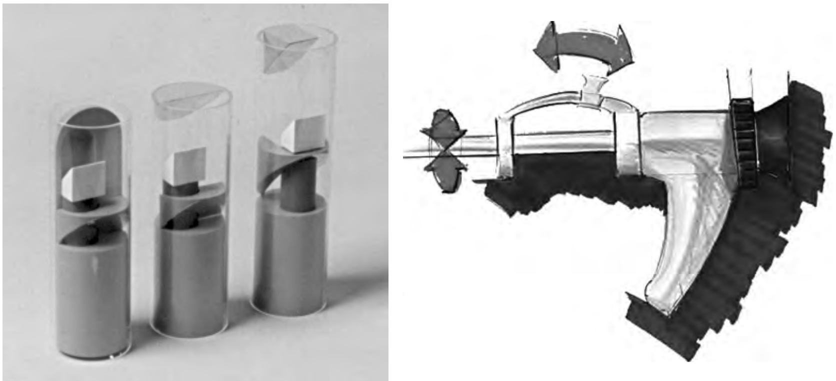

Figure 7.19
Three possible configurations of the tip of the borescope (left) and a designer's impression of the interface (right) [by Djajadiningrat].

designed to be replaceable, so that depending on the application the user can select a tip with the appropriate distance between the light sources. Fig. 7.19-left shows three prototypes of possible tip configurations.

The interface design takes into consideration the use to which the borescope will be put. A borescope is used in two ways: when a fault is suspected the inspector looks directly into the borescope, while for general inspection purposes the inspector uses a camera and monitor (Fig. 7.20). The handle was designed to suit both types of use.

For looking directly into the borescope the handle can be placed in the downward position so that it suits the way in which the inspector holds the borescope to his eye (Fig. 7.19). In the downward position the shape of the handle expressively shows this use. However, it also constrains the use of the borescope in two ways. First, it is impossible to link the motions of the light source to his head movements as the inspector will not move relative to the borescope. Therefore a control device was designed whose circular shape reflects the (simulated) movements of the light source, and which can be manipulated by hand (Fig 7.19). Second, the shape of the handle makes it difficult to change the viewing direction of the borescope, i.e. to rotate the borescope around its longitudinal axis. Therefore, the tip was made rotatable relative to the borescope. To manipulate this orientation the tip was linked to the circular control device. The orientation of the control device relative to the longitudinal axis indicates the viewing direction (downwards in Fig 7.19).

For general inspection purposes the inspector uses a camera and monitor (Fig. 7.20). Instead of holding the borescope to his eye, the inspector now holds it at some distance. To enable this type of use Prototype 5, however, has a handle which can rotate relative to the borescope, and in which the camera is integrated (Fig 7.20). Rotating the handle upwards places the camera over the eye piece. Covering the eye piece removes the invitation to look directly into the borescope. Exposing the eye piece, by placing the handle in the downwards position, the inspector is invited to place it to his eye and look directly into the borescope.

Prototype 5 was built (Fig. 7.21, App. II-C shows the technical drawings). The diameter of this prototype was 25 mm, which was large enough to include a conventional 10 mm laparoscope (to obtain an image similar to a conventional borescope) and two light guides. The tip included three mirrors, one to redirect the viewing direction (in the middle) and two to direct the two light guides.

For a number of reasons, Prototype 5, and the implementation of shadow parallax for industrial application, was not developed further. While manufacturers showed interest they did not engage in further development. However, interest was shown for medical application. Moreover, Surgi-Tech,

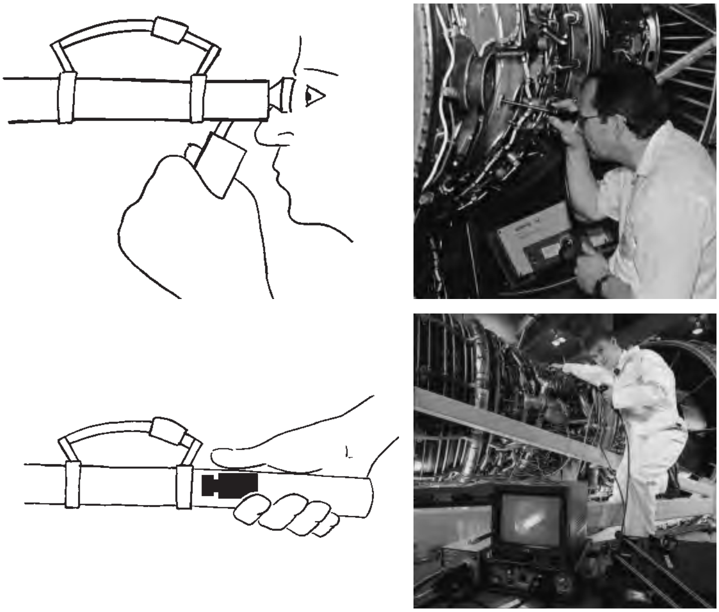

Figure 7.20
The shape of the borescope suits the two ways in which it is used: looking directly into the bore-scope (top), and using a camera (bottom).
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an American manufacturer of endoscopes, showed interest in building a prototype based on shadow parallax for medical uses.

In co-operation with Surgi-Tech, shadow parallax was implemented for medical application, Prototype 6. Medical laparoscopes are direct-viewing, i.e. the viewing direction is in line with the length of the laparoscope. Implementation of simulated shadow parallax, therefore, is constrained by the diameter of the laparoscope. Commonly the light guide terminates in a ring around the lens of the laparoscope. Simulated shadow parallax can be implemented by splitting the ring into two parts (Fig. 7.23). The amount of light depends on the area of the ring and the intensity of the light source. Preferably a laparoscope based on simulated shadow parallax will provide an amount of light which is (at least) equal to that of a conventional laparoscope. However, since the intensity varies, the total amount of light will be less if the sum of the area of the two light sources is equal to the area of the single light source of a conventional laparoscope.

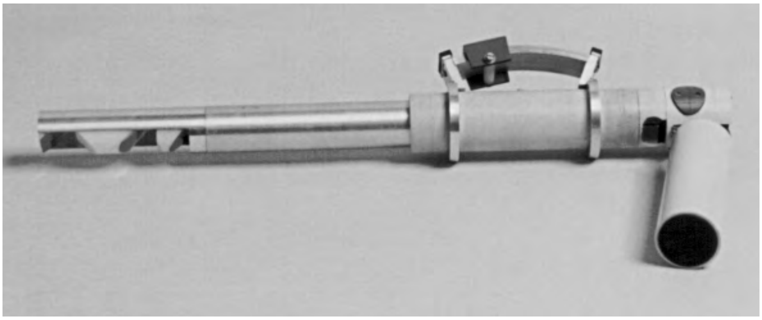


Figure 7.21
Prototype 5: a side-viewing industrial borescope based on shadow parallax.

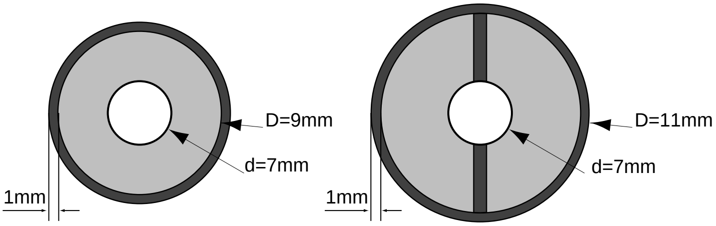


Figure 7.23
The tip of a conventional laparoscope (left) and the tip of the laparoscope with separate light guides (right). The area of the light guides was double which in total doubled the amount of light.

By slightly increasing the diameter of the laparoscope (from 10 mm to 12 mm) the amount of light was doubled. This was done to ensure that, even in the situation that one light source is at minimum intensity, the total amount of light is comparable to the amount of light produced by the single light source of a commonly used laparoscope. Therefore, the area of each light source should be equal to the total area of the single light source. The area of a single light source is approximately 32 mm^2 (the diameter of the lens is approximately 7 mm, and the outer diameter of the light guide is approximately 9 mm). Increasing the laparoscope's diameter by 2 mm from 10 mm to 12 mm doubles this area. While the lens diameter remains 7 mm, the outer diameter of the light source becomes approximately 11 mm, which means that the area of the light source becomes approximately 72 mm^2.

Fig. 7.24-left shows a close-up of the tip of a commonly used 10 mm laparoscope with a single light source, and Fig. 7.24-right shows Prototype 6 with the two separate light sources. Prototype 6 was tested in a laboratory set-up and in a practical setting at the laboratory for Experimental Surgery at Academic Medical Centre, University of Amsterdam (AMC/UvA). In the laboratory set-up the variations in the balance of the intensity of both light sources was visible, but in the practical situation it was not. Compared to the movements of the organs inside the abdomen caused by heart beat and breathing, the variation in the balance of the intensity of the light sources was not visible.

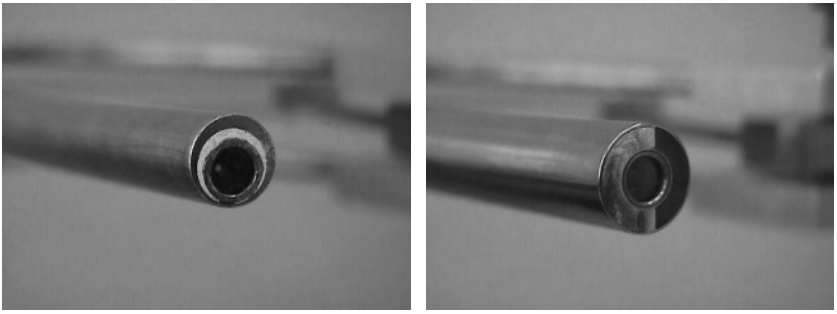


Figure 7.24
the tip of a conventional laparoscope (left) and the tip of the laparoscope built by Surgi-Tech (right).

7.2.4 Moving the entire laparoscope

Experiments described in Chapter 6 indicated that for medical application a laparoscope based solely on shadow parallax shadow is not feasible. Instead the surgeon should be provided with control over the point of observation (viewpoint parallax). Based on the results of Exps 5 and 6 the following was concluded:

- Viewpoint parallax is feasible for observation and/or manipulation tasks whereas shadow parallax is not. Results suggest the advantage of a combination of both principles (Exp. 5).
- The performance of an observation task is not affected by an assistant directing the laparoscope (Exp. 6).
- When performing a manipulation task the laparoscope should be supported mechanically (Exp. 6).

This section will describe a prototype which provides the surgeon with control over the point of observation, and which supports the laparoscope.

7.2.4.1 Rotating around the abdomen wall

The experiments described in Chapter 6 allow for a more accurate description of the third criterion given in the introduction to this chapter, i.e. the implementation should provide sufficient information to perform the task. The performance of an observation task is not affected by movements generated by an assistant directing the laparoscope, but the performance of a manipulation task is. During manipulation the surgeon should have sole control over the movements of the laparoscope (Ch. 6). Previous propositions for technical implementations of viewpoint parallax have focused on a laparoscope which has a built-in movable camera, or a laparoscope the entire tip of which (including the camera) can move. If the assistant is to be omitted, then apart from designing a laparoscope which allows exploration it is also necessary to design a mechanism to support it. Both criteria, allowing the surgeon to explore and supporting the laparoscope, were integrated into one mechanism by making use of the laparoscope’s fish-eye lens.

The object of the DVWS is to allow explorative movements around a fixation point. For example, Fig. 7.26 shows five different monitor views of a cube resulting from such explorative movements. Previous prototypes were based on two rotation axes (for example Fig. 7.4: Prototype 1). One of these rotation axes can be omitted if the laparoscope is allowed to rotate around the abdomen wall (Fig. 7.12). As a result a laparoscope with only one rotation axis is needed, but an additional mechanism will be needed to rotate the laparoscope around the abdomen wall, in synchrony with the movements of the tip.

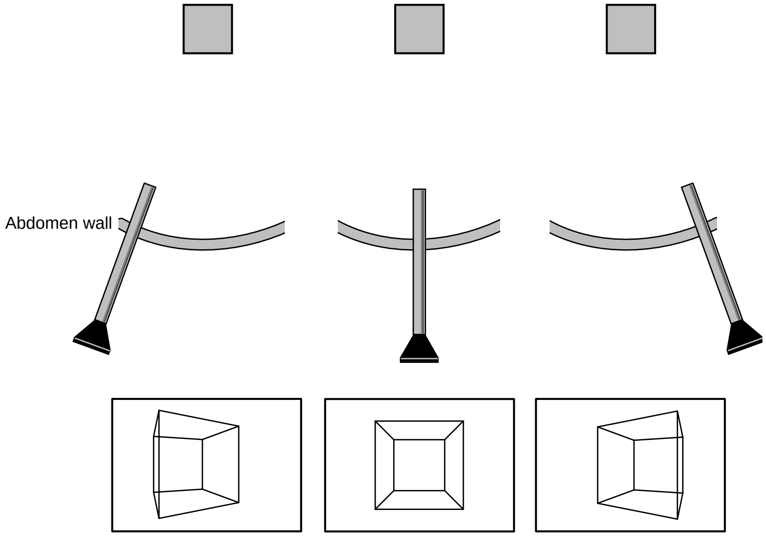


Figure 7.26
The movements of a laparoscope around a fixation point. The cube, at which the laparoscope remains aimed, is observed from different points of observation (top) and the corresponding monitor images (bottom). If the DVWS were implemented in this way, laparoscopy would not be minimally invasive.

Instead of a laparoscope with a movable tip exploration is also possible using a commonly used rigid laparoscope by rotating the laparoscope around the abdomen wall (Fig. 7.27). A commonly used laparoscope has a fish-eye lens with a viewing angle which can vary from 60° to 120°. This fish-eye lens makes it possible to direct the tip of the laparoscope away from the area of interest, while keeping it within the field of view. Since the point of observation is located at the tip of the laparoscope, rotating the laparoscope around the point of entrance of the abdomen results in a translation of the point of observation. The area of interest is observed from a different angle.

Rotating the laparoscope around the point of entrance of the abdomen differs from the original idea of the DVWS in that the camera does not make a

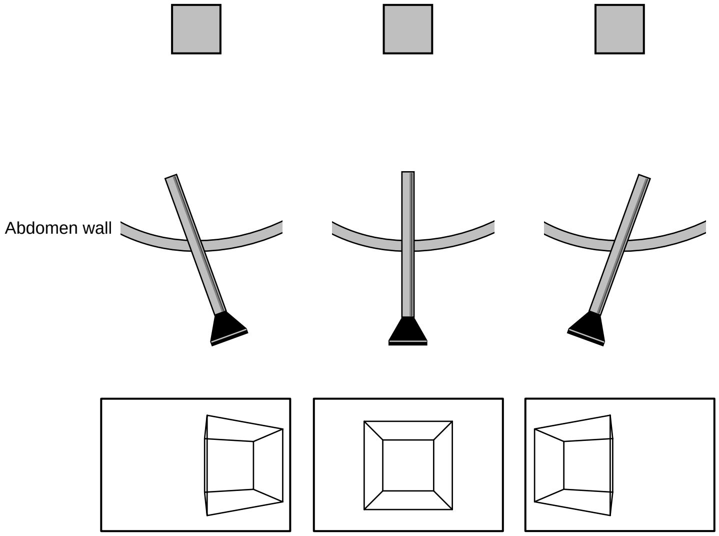


Figure 7.27
Movements of a laparoscope when rotated around the abdomen wall (top) and the corresponding monitor images (bottom).

circular movement around a fixation point. As the laparoscope rotates around the abdomen wall, there is no stationary fixation point within the field of view. Instead, the object of interest shifts towards the edge of the monitor screen, to the region with the largest deformations. This is different from the original implementation [App. I, Smets 1995, Overbeeke *et al.* 1986]. Originally the fixation point (i.e. the point at which the camera is aimed) and the rotation point (i.e. the point around which the camera rotates) coincide. The fixation point is then stationary relative to the scene displayed on the monitor and relative to the monitor itself. As a result the fixation point links the spatiality of the observed scene to the movements of the observer. When using the fish-eye lens the fixation point and the rotation point do not coincide. But although the two points do not coincide, the spatiality of the observed scene is still linked to the movements of the observer because the point of rotation is indicated by the shifts during camera movements (Fig. 7.28).

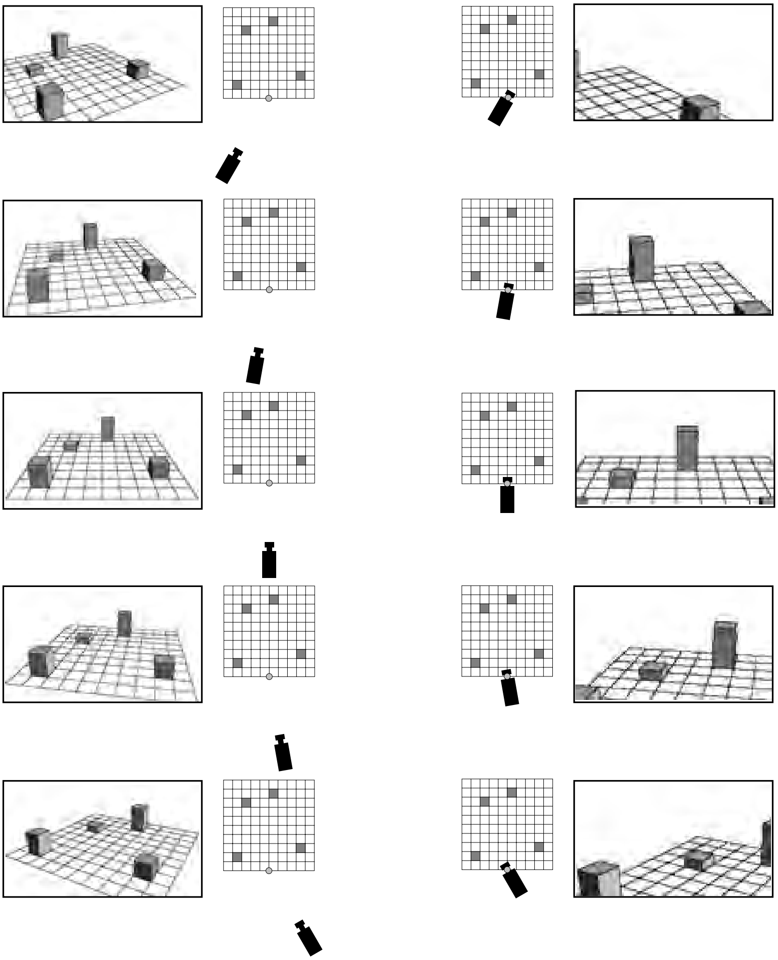


Figure 7. 28
Views when the camera moves according to the DVWS, i.e. when the fixation point and the point of rotation coincide (left). Views when the camera moves similar to the proposed movements of the laparoscope, i.e. when the fixation point and the point of rotation do not coincide (right). Although both points do not coincide the point of rotation (which is located at the abdomen wall) is implied by the shifts within the monitor image.

There are two ways in which the rotation of the laparoscope around the abdomen wall can be linked to the head movements of the observer (Fig. 7.29). First, the tip of the laparoscope and the observer can be linked so that the tip moves in the opposite direction to the head movements of the observer (Fig. 7.29-left). This way of linking has the effect of allowing the observer to look around as if at a panorama. For example, when the observer moves to the right, the monitor will present a view of the left side of the abdomen. The disadvantage of this way of linking is that the observer has to move counter-intuitively to explore an area of interest located close to the laparoscope (such as during manipulation). For example, to observe an area of interest from the right, the observer has to move to the left.

Second, the tip of the laparoscope and the observer can be linked so that the tip moves in the same direction as the head movements of the observer (Fig. 7.29-right). This way of linking has the effect that the observer can not look around, as at a panorama. Thus, when the observer moves to the right, the monitor will present a view of the right side of the abdomen. The advantage of this way of linking is that the movements to explore an area of interest located close to the laparoscope correspond to normal explorative movements. For example, to observe an area of interest from the right, the observer has to move to the right.

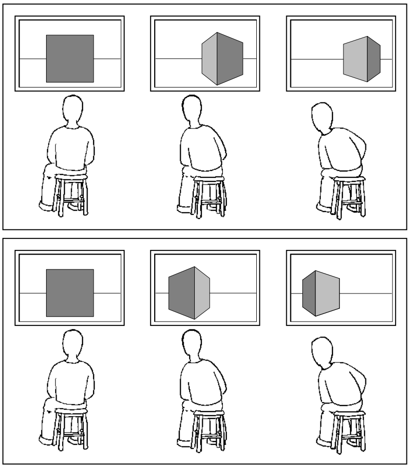


Figure 7.29

The tip of the laparoscope can be made to move either in the opposite direction to the observer (left), or in the same direction as the observer (right).

Whether the tip of the laparoscope should be made to move with the observer was tested with a simple laboratory set-up (Fig. 7.30). The image was obtained using a 10 mm laparoscope, with a 70° field of view. Observers preferred the tip of the laparoscope to move along with their head movements. The same set-up was used to demonstrate that the fixation point and the rotation point do not have to coincide. Observers were found to be able to explore a scene.

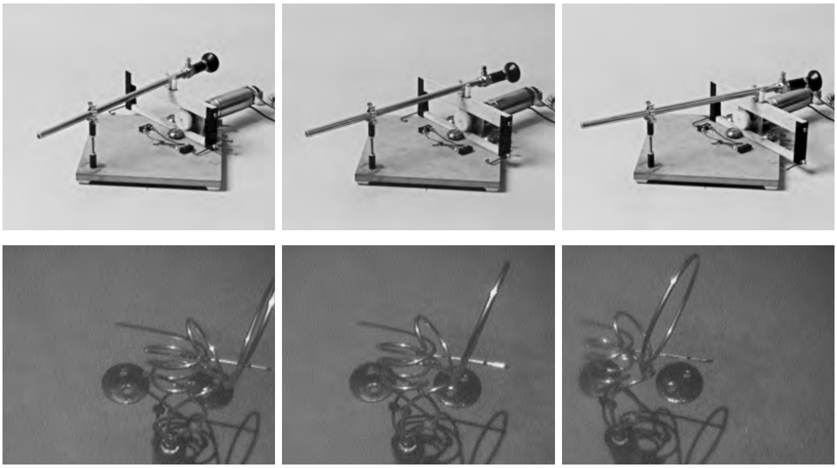


Figure 7.30 *Mechanism to test rotating the laparoscope around a point of entrance (top) and a set of corresponding monitor images (bottom).*

7.2.4.2 Moving the entire laparoscope

The advantage of rotating the laparoscope around the point where the trocar enters the abdomen, is similar to the advantage of shadow parallax in that rotating a common laparoscope requires no moving parts within the laparoscope because it virtually removes all limitations in respect of the mechanism. For example, Finlay *et al.* [1995] exploit the freedom with respect to the size of the mechanism and use an industrial robot for controlling the motions of the laparoscope. However, a large industrial robot may not be the best of solutions. In our case, for instance, the mechanism needs if possible to be small and simple so that it can be manipulated by the surgeon.

Two mechanical solutions were explored for rotating the laparoscope around the point where it enters the abdomen. Either a rotation point was transposed using a parallelogram (Fig. 7.31-left), or a prefabricated circular guide was used along which the laparoscope could move (Fig. 7.31-right). Both were designed from the idea that the mechanism should be connected to the laparoscope rather than the trocar. This means that when the laparoscope is removed the mechanism which controls its movements will be disconnected as well. This allows for simple removal and relocation of the mechanism, for example, when the laparoscope enters the abdomen through a different trocar.

A parallelogram (Prototype 7, Fig. 7.32) has a number of advantages over the circular guide. It is simple to construct, since it consist merely of straight elements, and it is small. Also, compared to a circular guide, the parallelogram only has rolling parts and such a design can be used to implement perfectly smooth movement. A disadvantage is that spindles are difficult to sterilise. For thorough sterilisation, these spindles should preferably be removable so that they can be sterilised separately. Prototype 7 (Fig. 7.32) is designed so that all

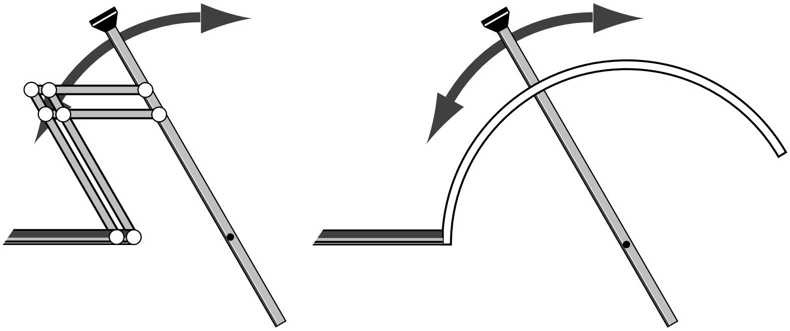


Figure 7.31
Two theoretical solutions: a parallelogram (left) and a prefabricated circular guide (right).

moving parts can be disassembled. It is assumed that the motor controlling the motions of the laparoscope will have to be removed before sterilisation. Prototype 7 is designed so that by removing the motor it splits into its elements. Dismantling is simple, but reconstructing the mechanism is like a jigsaw puzzle in a way that is not self-explanatory (Fig. 7.33). Another disadvantage is that the parallelogram is less expressive in showing how it has to be located relative to the trocar. Its shape does not show the location of the parallelogram relative to the location of the trocar.

A circular guide (Fig. 7.31-right) has the advantage over the parallelogram that the circularity of the guide expressively shows the motions of the laparoscope, and the position of the guide relative to the trocar, namely that the trocar is at the centre point. Disadvantages are its relatively large size and the technical implementation for controlling the motions of the laparoscope along a circular path. Controlling these motions has two parts: the laparoscope has to be directed to move along the circular guide, and these movements have to be linked to the surgeon's head movements. For directing the laparoscope along the guide a trolley is used. The trolley has no wheels or rolling parts. Instead, it is made of Poly Oxy Methyleen (POM) to make it shift easily along the (steel) guide. For controlling the motions along the guide a parallelogram is used. This is driven by a motor located at the root of the circular guide. This

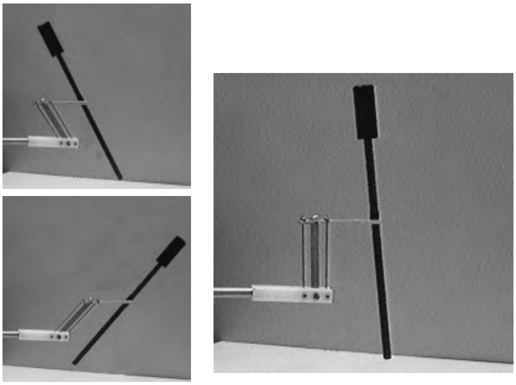


Figure 7.32
Prototype 7: moving the laparoscope by means of a parallelogram.

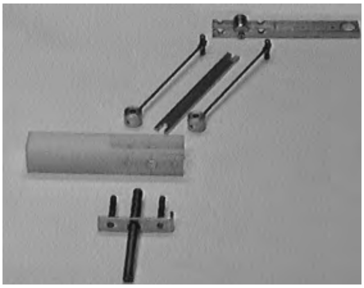


Figure 7.33
Prototype 7 can easily be taken apart but putting it back together again is like solving a jigsaw puzzle.

parallelogram, since it does not have to support the laparoscope, is lightly constructed. Fig. 7.34 shows Prototype 8, which is based on the circular guide. Prototype 8 was tried by an experimental surgeon at the laboratory for Experimental Surgery at Academic Medical Centre, University of Amsterdam (AMC/UvA). As it was built with the purpose of merely demonstrating the shape and function of the circular guide, when put to the test it initially showed some technical imperfections. The motor used could hardly move the laparoscope because of high friction between the trolley and the guide. This high friction also caused the gearwheel on the motor axis to slip. However, it was found possible to reduce the friction after which the mechanism was found to work properly. The surgeon indicated that the mechanism allowed him to look around.

Both prototypes, the parallelogram (Prototype 7) and the circular guide (Prototype 8), do not leave fragments, can be sterilised, and allow the surgeon to explore. The circular guide is preferred for its usability. The advantage over the parallelogram is that the circular guide expressively shows how the laparoscope is going to move, and how it should be located relative to the trocar. Furthermore, it has a rigid frame which provides sufficient grip during installation. In addition, the circular guide looks more friendly because its

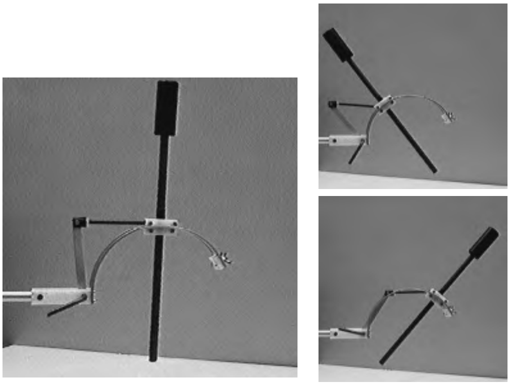


Figure 7.34
Prototype 8, based on the circular guide (the diameter of the circular guide is approximately 16 cm).

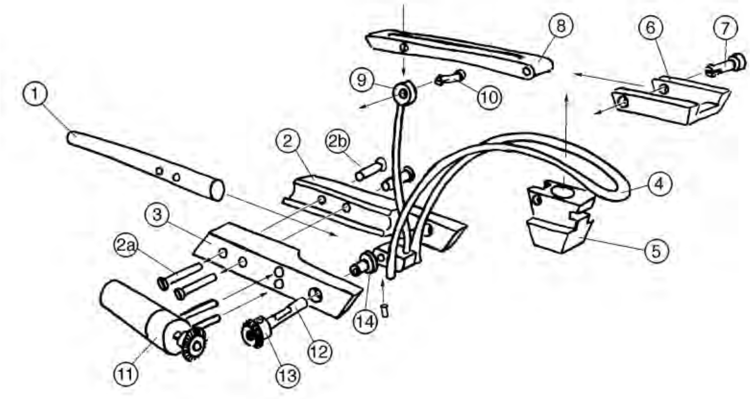
round shape fits the organic form of the patient, unlike the sharp and straight parallelogram. The circular guide (Prototype 8) will be developed further, into a fully functional prototype. This will be described in the next section.

7.3 A circular guide (Final prototype)

7.3.1 The circular guide described in detail

A final prototype of the circular guide based on Prototype 8 was designed and built. (Fig. 7.35 shows an exploded view of the final prototype, see App. II-D for the technical drawing.) This prototype was designed for ease of assembly and disassembly, so it can be easily taken apart for cleaning and sterilisation. Its components can be divided into four groups: the body, the trolley which moves along the circular guide, the parallelogram to drive the trolley, and the motor to drive the parallelogram. How each of these groups was designed to allow for simple operation will be described in more detail below (the numbers refer to Fig. 7.35).

The body consists of four elements: a round rod (1), one body part, which in Fig. 7.35 is drawn as two pieces (2 and 3), and the circular guide (4). To minimise friction between the plastic trolley and a circular guide, the guide is made out of steel. The circular guide is glued to the body of the device and the body is mounted on the round rod by means of two nuts and bolts (2a and 2b). This allows replacement of the round rod, for example by a rod of a different length. When put together, the body is one rigid unit.



1	Rod
2	Body
2a	Bolt
2b	Nut
3	Bobby
4	Circular guide
5	Trolley-main part
6	Trolley-lock
7	Hinge axis
8	Horizontal rod
9	Vertical rod
10	Hinge axis
11	Motor and mounting bracket
12	Mitergear
13	Rotation axis
14	Bearing

Figure 7.35
An exploded view of the final prototype based on a circular guide.

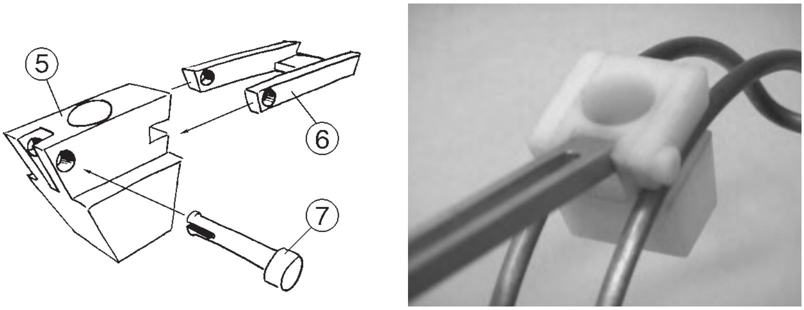


Figure 7.36
The trolley is made out of two parts held together with a hinged spindle. Removing this spindle means that the trolley can be removed from the circular guide (the numbers refer to Fig. 7.35).

The trolley (Fig. 7.36), which is made out of POM to reduce friction with the circular guide, consists of three parts: the main part (5), the lock (6) and a hinged spindle (7). The main part is, inserted into the circular guide (4) from below, after which the lock is fitted onto the trolley's main part. These parts are held together with a hinge axis (7). The trolley has a circular shaft, through which the laparoscope can be inserted. Since laparoscopes can differ in diameter, the inner diameter of the shaft may have to vary. This can be solved in two ways. First, since the trolley can easily be removed and replaced, it is possible to have a set of trolleys, each having a shaft with a specific diameter. Second, there can be a set of tubes, which can be inserted into the trolley, each of the tubes having a different inner diameter. Then, when a smaller diameter is needed, a different tube can be inserted. Fig. 7.37 shows two such tubes. The advantage of a set of tubes compared to a set of trolleys is that a tube will be less difficult to change at the operating table. However, because the diameter of the laparoscope used will be known prior to the operation, both solutions are feasible.

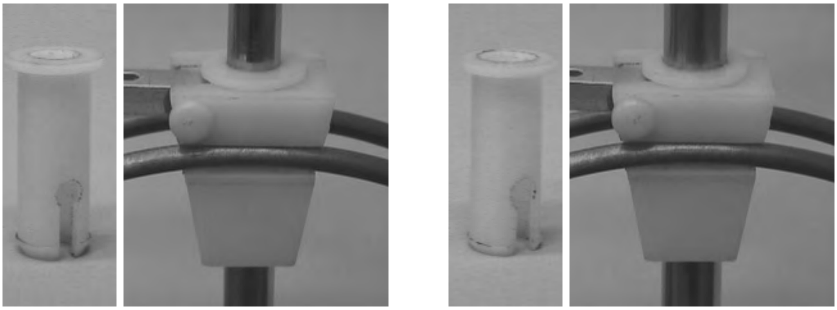


Figure 7.37
Two examples of a tube to adapt the inner diameter of the trolley to the diameter of the laparoscope used.

The parallelogram consists of three parts (Fig. 7.38): the horizontal bar (8), the vertical bar (9) and a hinged spindle (10) connecting both bars. The horizontal bar rotates around the same hinged spindle (7) that is used to connect the bar with the trolley and to hold together the trolley's main part (5) and its lock (6). A similar hinged spindle (10) is used to connect the horizontal and vertical bar.

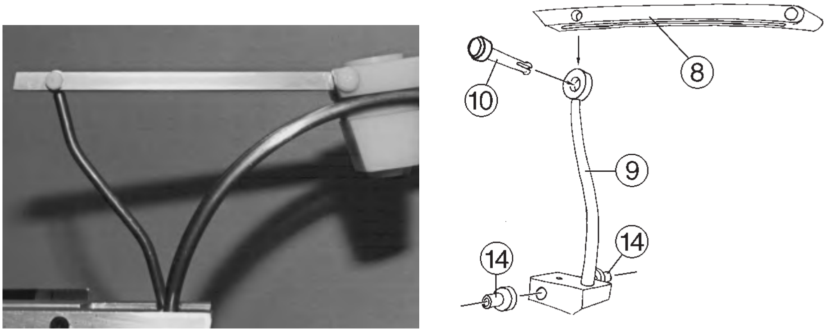


Figure 7.38
The parallelogram connecting the trolley to the motor (the numbers refer to Fig. 7.35).

The motor and mounting bracket are shown in Fig. 7.39. To minimise the width of the mechanism, the motor is placed parallel to the round rod (1) and at a small distance from the body, to make the prototype look less heavy. The motor is connected to the body with two bolts, and can be attached on both sides of the body. The motor drives a rotation shaft (12 and 13) upon which the vertical bar is connected (9). This rotation shaft has two plastic bearings (14) which, together with the vertical bar, fit the space between both sides of the body (2 and 3). Thus the rotation shaft, after the vertical bar is mounted on it, cannot translate and its only degree of freedom is rotation.

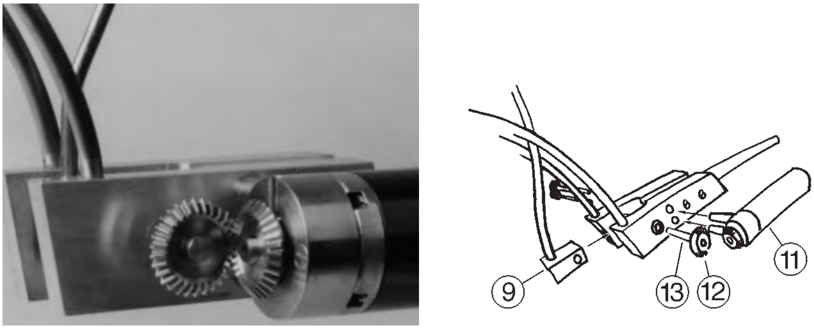


Figure 7.39
The motor mounted to the side of the body (the numbers refer to Fig. 7.35).

Those parts of the instruments that may come into contact with either the surgeon, the patient, or an instrument that can make contact with either one of them, have to be sterile. Other parts only have to be clean. The main problem for sterilisation and cleaning is movable parts, such as rotating shafts and bearings, if they cannot be dismantled. Therefore, all movable parts of the prototype can be dismantled, for which only three bolts, and two pins have to be removed. The motor is connected to the body by two screws (2a and 2b, in Fig. 7.35). The vertical bar (9) and the spindle (12 and 13) are connected to the body with one bolt. The parallelogram and the trolley are kept together with two hinged spindles (7 and 10). Removing these bolts and hinged spin-

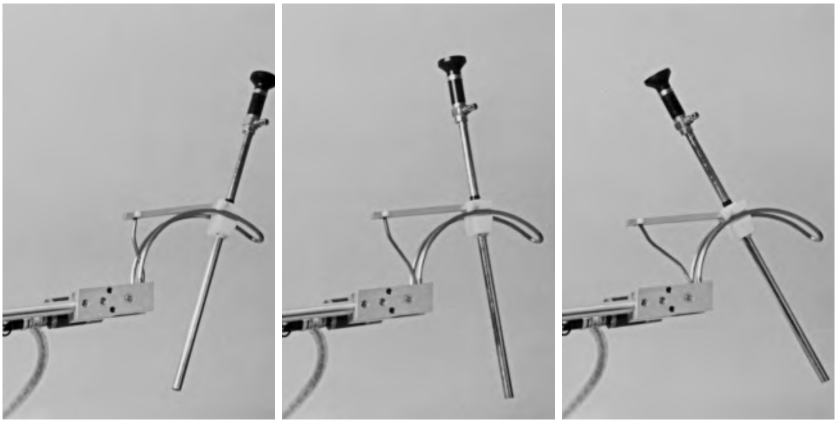


Figure 7.40 *The final prototype of the circular guide. It clearly shows the movements of the laparoscope around the centre of the circular guide.*

dles leaves seven parts of the mechanism and two bearings, which can be sterilised separately. Fig. 7.40 shows the final prototype.

7.3.2 Mounting the circular guide

Exp. 6 (Ch. 6) showed that during a manipulation task the laparoscope should not be directed by an assistant but should be mounted in a mechanical support. When the laparoscope is mounted in a mechanical support, the assistant may only be needed to adjust this support and redirect the laparoscope towards a new area of interest. However, it is more likely that the redirection of the laparoscope will also be done by the surgeon. The assistant, who will not be needed to hold and direct the laparoscope, will probably attend to other tasks, and therefore may not be around to redirect the laparoscope, which may invite the surgeon to redirect the laparoscope himself. Therefore, when designing a prototype which allows the surgeon to explore, a mounting device should also be designed to allow the surgeon to redirect the laparoscope towards a new area of interest.

Redirecting the laparoscope can be performed by adjusting the orientation and translation of each axis individually. However, Djajadiningrat *et al.* [1997c] showed that adjusting a spatial orientation is better done by freely rotating the entire object at once. Thus, all adjustable degrees of freedom have to be released and constrained at once. When redirecting the laparoscope there are six degrees of freedom, three rotations and three translations (Fig. 7.41-left). A laparoscope inserted in the trocar is constrained in two directions, namely the translations in the x direction and in the y direction. A laparoscope thus has four degrees of freedom: three rotations (one around each axis), and one translation (in the viewing direction of the laparoscope). Three of these are constrained by the mounting device, namely the rotations around the three axes.

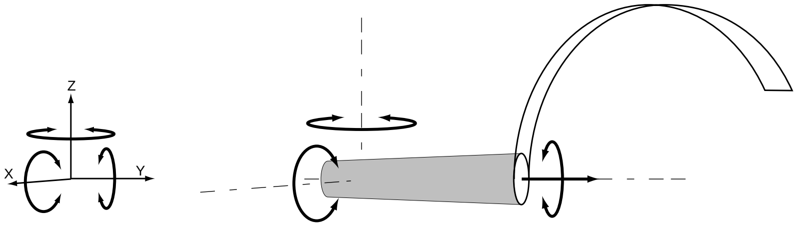


Figure 7.41
Six degrees of freedom: three translations and three rotations (left) and the four degrees of freedom to be operated by the surgeon: one translation and three rotations (right).

Redirecting the laparoscope can be regarded as two types of adjustments: first, adjustments corresponding to horizontal shifts on the monitor screen, and second, adjustments which do not correspond to horizontal shifts. Horizontal shifts are achieved because movements of the laparoscope in this direction are linked to the head movements of the surgeon. Therefore, redirecting the laparoscope in this direction can be realised by unlinking the motor. For example, a small sensor can measure whether the surgeon is holding the laparoscope in his hand. If the surgeon is holding the laparoscope then the motor is unlinked, and as soon as the surgeon releases the laparoscope the motor is linked to the his head movements.

Adjustments in directions which do not correspond with horizontal shifts on the monitor are, for example, adjustments in the direction corresponding to vertical shifts on the monitor screen, or adjustments in the direction from and towards the area of interest. Such adjustments are more difficult to realise since they require reorienting or translating the entire circular guide. It thus requires control over the mounting device which connects the circular guide to the operation table.

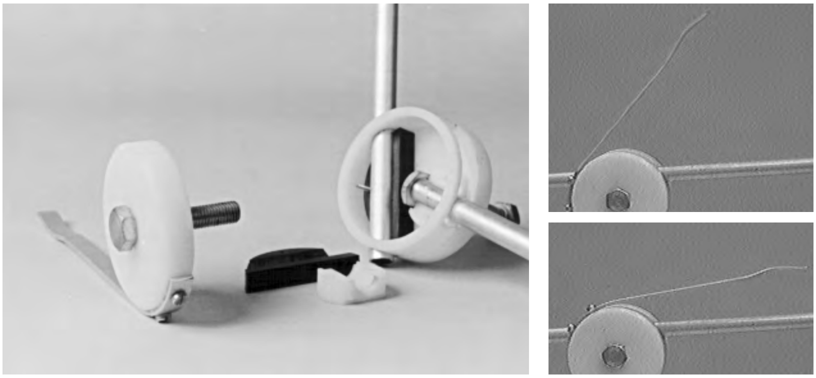


Figure 7.42
Prototype 9, a mounting device which makes it possible to constrain and release four degrees of freedom (three rotations and one translation) with one hand movement.

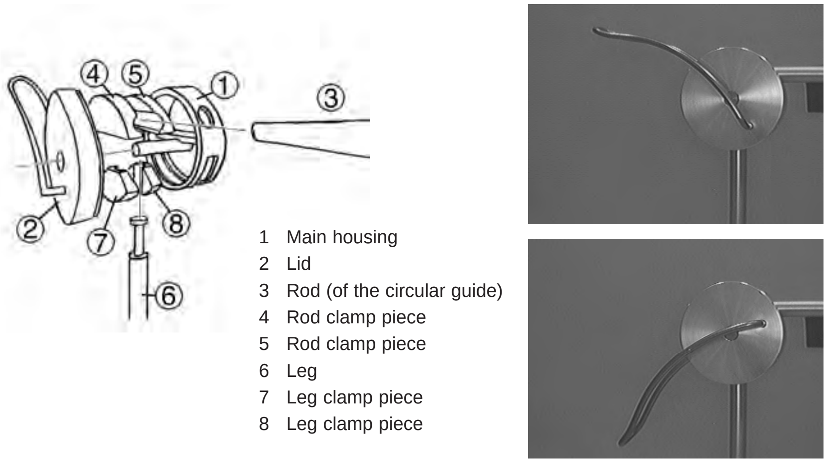


Figure 7.43 *Prototype 10: the mounting device based on Prototype 9. an exploded view (left). To lock the mounting device the grip has to be rotated up-wards (right-top), and to lock it the grip must be rotated downwards (right-bottom).*

Prototype 9, shown in Fig. 7.42, is a support which releases and constrains the three rotations with one action. By pushing the handle downwards the three rotation degrees of freedom are locked. One translation degree of freedom is also locked, to restrict the translations of the circular guide in the horizontal direction. Pulling the handle upwards releases all degrees of freedom. The mounting device is designed with only six components so that it can be taken apart for cleaning or sterilisation. Based on this initial prototype, a mounting device was designed and built (Prototype 10, Fig. 7.43).

Prototype 10 differs from Prototype 9 in one way, namely in the shape of the handle. This was pointed forwards in Prototype 9, but now points backwards. The shape was changed because in the locked position the handle could clash with the motor of the circular guide. The handle of Prototype 10 accordingly points backwards, away from the circular guide. Now, when the handle is pointed upwards, all degrees of freedom are locked. In this position the shape invites pushing. When the handle is pointed downwards, the four degrees of freedom are unlocked. Now, its shape invites lifting. The technical drawings can be found in App. II-E.

7.3.3 Head tracking

To link the laparoscope to the surgeon, the surgeon’s head movements need to be tracked. For this a number of technical devices are available, such as a camera device [Stappers, 1997], a magnetic measuring device or an infra-red detection device. Of these the infra-red detection device is the most practical. Its advantage is that it requires the surgeon to wear a small reflector only. Nowadays, to protect against possible infection, such as AIDS, surgeons have to wear safety glasses upon which a small reflector may easily be placed.

One concern is that when the movements of the laparoscope are linked to the head movements of the surgeon the laparoscope will make uncontrolled movements when the surgeon is not looking at the monitor but, for example, turns his head or walks away. Therefore, the infra-red detection device was tested for two situations, namely sensitivity to rotations of the sensor around its vertical axis, and the rotations of the sensor around the tracking device. For each situation two angles were measured: the angle at which the reflector goes out of track, i.e. when the tracking device cannot locate the reflector, and the angle at which the tracking device, after being out of track, picks up the reflector again, i.e. the angle at which the tracking device relocates the reflector.

Rotations of the reflector around its vertical axis can be up to 40° sideways (80° in total) without going out of track (Fig. 7.44). Thus the surgeon does not have to keep his head aimed at the monitor, but can rotate his head away without losing control over the movements of the laparoscope. However, when the surgeon is out of track, i.e. when the tracking device cannot locate the reflector, he will have to look at the monitor in order to regain control over the laparoscope. This area is shown grey in Fig. 7.44. The reflector has to be pointed towards the tracking device before it can be relocated.

Rotations of the reflector relative to the tracking device can be large: up to 20° sideways (40° in total) without going out of track, so the surgeon can make movements relative to the monitor without losing control over the laparoscope. For a distance between the surgeon and the tracking device of 2 metres, the surgeon can move within an area of 0.7 metres to left and right relative to the centre of the monitor (on top of which the tracking device is located), without losing control over the laparoscope. Should the surgeon go out of track by moving out of the area where the tracking device can pick up the location of the reflector, control is immediately restored when he returns to this area, since the angle of going out of track and the angle at which the location of the reflector is picked up are almost equal (20° vs. 19°).

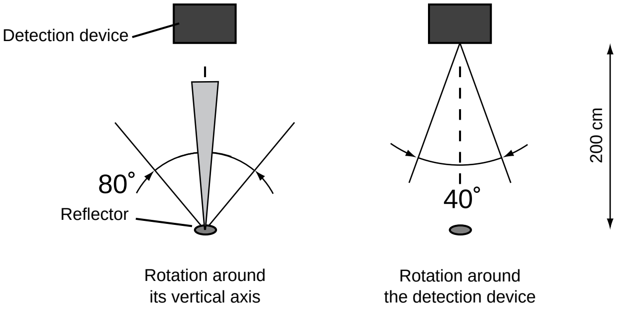


Figure 7.44
The sensitivity of the infra-red detection device when the reflector is at a distance of 2 metres under normal room illumination. A reflector with a diameter of 10 mm was used.

In conclusion, the surgeon has control over the laparoscope provided that he keeps looking at the monitor and provided that he remains within a distance of 0.7 metres to the left and to right of the centre of the monitor. When he goes out of track, the surgeon has to look at the monitor or move towards the area in front of the monitor screen before regaining control over the movements of the laparoscope. Note that the values presented here were obtained in a laboratory. In the operating theatre the illumination will be different, which may affect these values.

7.4 Evaluation in a practical setting

The circular guide and the mounting device were tried out by an experimental surgeon in a practical setting at the AMC/UvA. Fig. 7.45 schematically shows the set-up during the experiment.

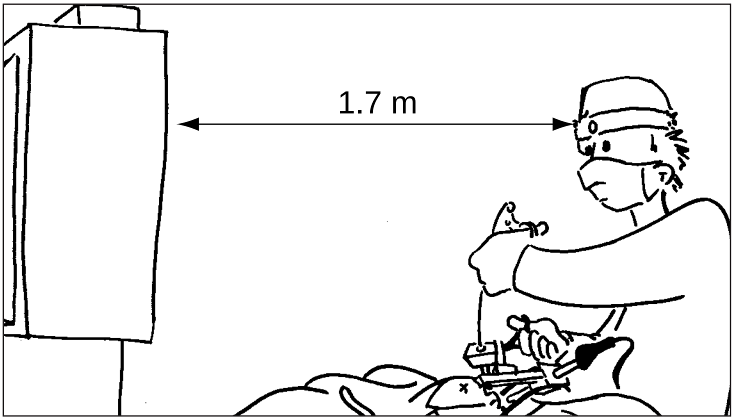


Figure 7.45
A schematic overview of the situation during the evaluation test.

The mounting device was attached to the side of the operating table, and the circular guide was placed in the mounting device. As discussed in the previous section, two types of readjustment may occur, namely readjustments in the horizontal direction, along the circular guide, and readjustment in a direction other than the horizontal. For readjustments in the horizontal direction a button was placed on the outer end of the laparoscope which, when pressed, unlinked the laparoscope and the surgeon (Fig. 7.46). Pressing this button allowed the surgeon to move the laparoscope freely in the horizontal direction. By releasing the button the laparoscope was again linked to the surgeon. For readjustments in a direction other than the horizontal, the orientation of the circular guide had to be changed, for which the mounting device has to be used. It could be changed by unlocking the circular guide from the mounting device, then changing the orientation of the circular guide, after which it had to be re-locked in this new orientation. Unlocking and locking could be done with one hand while using the other for reorienting the circular guide.

Figure 7.46
A button, to temporarily disconnect the surgeon from the laparoscope, was placed at the end of the laparoscope. When holding the laparoscope, the button is automatically pressed (right), and the laparoscope can move freely.

An infra-red detection device was used to measure the head position of the surgeon. A concern that was raised in section 7.6.3 was that the illumination in the operation room may limit the range of the tracking device. A reflector with diameter of 10 mm was used, which remained in track. However, there were some irregularities in the tracking of the reflector. A book had to be placed on top of the tracking device, like a sun shield, because initially the device continuously indicated that it had the reflector within range, even if there was no reflector available to be tracked. The shield solved this problem. A new reflector, tried on a later occasion, did not display these irregularities.

The evaluation test started with the insertion of the first trocar. After the abdomen was inflated the circular guide was placed over the trocar. The laparoscope was inserted through the trolley and the trocar. The space between the inner diameter of the trolley and the outer diameter of the laparoscope was small enough for the laparoscope to remain fixed to the trolley. Fig. 7.47 gives the situation during the evaluation test.

The experimental surgeon started the try-out of the prototype by looking around, followed by a small manipulation task. Initially, the transmission ratio between the head movements and the rotations of the laparoscope was found to be too small, and it was increased. After trying the link with the laparoscope, two extra trocars were placed to insert two instruments. The size of the circular guide was found to be slightly too large for comfortable operation. The surgeon noted that the abdomen of a human is larger than the abdomen of the pig, and he expected that the circular guide would allow comfortable operation on a human. With the two instruments inserted the surgeon performed a small manipulation task (dissecting a part of the spleen). This was done without being assisted in operating the laparoscope or the mounting device. The head-tracking device worked properly, allowing the surgeon to turn his head and even walk away and return.

Figure 7.47
The final prototype is tested in a practical setting at the AMC/UvA.

During the test, some adjustments were made to the viewing direction of the laparoscope. For adjustments in a direction other than the horizontal the surgeon had to use both hands. However, during the evaluation test the mounting device was not used to change the orientation of the circular guide. Instead, all adjustments were performed directly on the laparoscope. With one hand, the surgeon forced the laparoscope to a new orientation, while with his other hand he held both instruments. After the operation most connections between gear wheels and shafts of the circular guide showed some play. The mounting device, although it was not used during the operation, was found to make it easy to position the circular guide at the beginning of the operation.

Overall, the surgeon was enthusiastic about being linked to the laparoscope. Being linked and controlling the movements of the laparoscope in the horizontal direction allowed him to look around and to explore, but he suggested that a coupling in the vertical direction could be preferable, as well as a coupling in the direction from and towards the monitor (zoom).

7.5 Discussion and conclusions

The main problem when implementing perception-action coupling for laparoscopy with respect to visual information consists of finding a technical implementation that allows exploration. In this chapter three types of technical implementations were described: implementations based on a camera that makes a circular movement around a fixation point, implementations based on simulating a moving light source (shadow parallax), and implementations based on rotating a laparoscope around the point where it enters the abdomen.

All the implementations described fulfil the first of the three criteria given at the beginning of this chapter: they provide the information to perform the task, they do not harm the patient, and they are usable. In this chapter, usability has been the most important criterion. In Chapter 2 a device was said to be usable when, with respect to its functions, the device showed its control and controlled actions, both for the spectator and the operator. Here, the control actions are hand movements to select an area of interest, and head movements to explore the selected area of interest. For the spectator it must be perceivable how to direct or redirect the device towards the area of interest. For the operator it must be perceivable how to explore the area of interest. When designing for interaction, the focus of attention shifts from the technical implementation towards use.

Based on usability, two implementations were selected, which were developed so as to fulfil the second criterion (it must not harm the patient). First, a direct viewing laparoscope based on shadow parallax was designed. This scope is similar to a conventional laparoscope, with the exception that the surgeon now has control over the illumination of his working area. Second, a circular guide was designed which can rotate a laparoscope around the point where it enters the abdomen. The circular guide alters the way in which the laparoscope is controlled, since now there is no assistant needed to hold the laparoscope. Instead, the laparoscope is mounted in a mounting device and the surgeon is provided with control over the movements of the laparoscope to explore an area of interest. However, apart from moving the laparoscope for exploration, the laparoscope also has to be directed towards the area of interest. A redirection of the laparoscope, since there is no assistant to hold it, can be expected to be performed by the surgeon as well. For this reason a mounting device was designed that can be controlled by the surgeon. The circular guide and the mounting device were both tested in a practical setting. It was found that the circular guide worked well, but that the mounting device did not. During the test all redirections were performed directly on the laparoscope. For this, a new solution may have to be designed.

CHAPTER 8

CONCLUSIONS

Affording action during Laparoscopy

This thesis discusses research aimed at the implementation of the DVWS [Delft Virtual Window System, App. I] for laparoscopy. Laparoscopy is a minimally invasive surgical technique, in the abdominal area, during which the surgeon operates through small “key-holes”. This technique has a number of advantages for the patient, including less dehydration, less damage to healthy tissue, a smaller risk of infection, and a shorter recovery period. For the surgeon, by contrast, there are no advantages, only disadvantages. For example, visual information is hampered - laparoscopes are commonly monocular, their fish-eye lens provides a distorted image, and they have a built-in light source, reducing shade and shadows. Moreover, since the surgeon needs both hands to operate, the laparoscope has to be aimed by an assistant. As a result, for the surgeon the perception-action coupling is distorted. Implementing the DVWS will restore the surgeon’s control over the laparoscope. This allows him, by making explorative head movements, to obtain spatial information and to relate the point of observation inside the abdomen to his own viewpoint (Ch. 3). The research on implementing the DVWS for laparoscopy has resulted in a working prototype.

This chapter starts with a reflection on the process of implementation, after which the implementation of the DVWS for laparoscopy is discussed. The chapter ends with recommendations for future research.

8.1 Implementing perception-action coupling

The structure of the thesis gives the illusion that the implementation progressed, starting with a theoretical framework, followed by experiments investigating possible technical solutions, and ending with implementations. But that is all it is: an illusion. Such a process may only be possible when, in advance, the problem (in this case the lack of depth perception during laparoscopy) is fully understood and its constraints on implementation are known. Here, they were not. On the contrary, a large part of the implementation consisted of understanding and outlining the constrains. The process can therefore best be described as an interaction between (1) the exploration of what kind of information to provide (perceptual criteria), which was done by exploring the relation between perception and action from a theoretical point of view and with feasibility studies, and (2) the exploration of how to provide this information (action criteria), which was done by exploring how to implement perception-action coupling into technical realisations.

The exploration of the relation between perception and action was done within the theoretical framework of the direct approach to visual perception [the direct perception theory, Gibson 1950, 1966, 1979]. The direct perception theory was found appropriate as a framework for implementation because it relates perceptual information and action possibilities. To describe this relation Gibson introduced the concept of affordances. Affordances are what the environment offers, or affords us, whether for good or for ill. In the light of this concept, implementation is a matter of creating the affordance appropriate to the task to be performed. The concept of affordance has been the subject of much debate, mainly with reference to its ontological status (the main question that is debated on is whether affordances are properties of the environment or of the relation between the observer and the environment) and how it relates to the intention of the observer. Here, for the purpose of guiding implementation, affordance is defined as a property of the environment, showing the possibilities for action within the environment (Ch. 2). The task to be performed was defined as complementary to the affordances, referring to what actions the observer wants to perform (Ch. 2). Affordances were operationalised with control actions (i.e. the actions performed by manipulating the device) and controlled actions (i.e. the functions of the device manipulated).

Implementation is not constrained only by the task, but also by the personal preference of the researcher. This is possible because there is commonly more than one way of improving the performance of a task, with respect to both the controlled action and the control action. For example, in the thesis two alternatives were investigated: controlling the point of observation and controlling the point of illumination. In Exp. 2 control over the point of observation was compared with control over the point of illumination (Ch. 5), and for both the performance was found to improve relative to the situation in which there was no control. The control action may also differ. For example, Pasman [1997] compared the situation in which the camera is linked to head movements to that in which it is linked to the rotation of a knob, and found similar performance. Between possible implementations that result in comparable task performance, a selection can be made using criteria such as energy consumption, the cost of fabrication or the availability of machinery. What gets most attention may be personal preference. In the thesis, in line with the concept of affordances, user-friendliness and self-explanatory operation were used as the criteria for choosing between comparable implementations. Using self-explanatory operation as a criterion has the advantage that the entire interaction between the user and the device is considered, i.e. not only whether the information it provides is sufficient, but also the way in which the information is obtained by the user. Implementation then becomes the design of an interaction, rather than the design of a technical realisation. The technical realisation then stays what it is: a technical realisation.

8.2 Affording action during laparoscopy

The aim of the project was the implementation of the DVWS for laparoscopy (Ch. 1); the result is a working prototype. As discussed in the previous section, implementation was an iterative process of feasibility studies, investigating perceptual criteria, implementation, investigating technical possibilities, and use.

From a perceptual point of view the DVWS has to provide the information needed to perform the task at hand. During laparoscopic operation two type of tasks are being performed: observation tasks and manipulation tasks.

The ability to explore, and hence the implementation of the DVWS, is an advantage when performing an observation task. In the first experiment it was found that for solving a spatial puzzle the DVWS is feasible (Ch. 4). However, implementation of the DVWS requires a complex mechanism inside the laparoscope (Ch. 7). For this reason the feasibility of an alternative principle providing similar perceptual information, shadow parallax, was explored. Shadow parallax is based on a moving light source which is linked to the head movements of the observer. Through making head movements the observer controls the shades and shadows within the scene observed. Its advantage over viewpoint parallax is that shadow parallax can be simulated by two stationary light sources of which the intensity balance varies (Ch. 5). Its implementation is therefore simple. Shadow parallax was found feasible for detecting differences in heights, but not for spatial observation tasks such as occur during laparoscopy. For these tasks it is better for the surgeon to control his point of observation inside the abdomen.

The ability to explore can be an advantage when performing a manipulation task. Initially, it was found that implementing the DVWS does not improve the performance of manipulation tasks because subjects simply do not move during precise manipulations (Ch. 4). This, however, has to be put in perspective. The performance of manipulation tasks depends greatly on whether an assistant holds the laparoscope, and on the amount of manual steadiness that is required for manipulation. If the laparoscope is held by an assistant, the performance of a manipulation task was found to decline compared to the situation in which the laparoscope is mounted in a mechanical support (Ch. 6). When manipulation requires steadiness of the hand, subjects will concentrate on manipulation and will sit as still as possible (Ch. 4). However, subjects who have experience with the instruments do make use of the ability to explore (Ch. 6). This suggests that improving visual perception by providing the surgeon with direct control over the movements of the laparoscope also includes redesigning laparoscopic instruments. During this research, the redesign of instruments was explored only sporadically [e.g. Maase, 1997]. The principal focus of attention was providing the surgeon with the control over his point of observation inside the abdomen.

From a technical point of view, implementing the DVWS for laparoscopy has one major difficulty, namely the creation of a circular movement of a camera (located in the tip of the laparoscope) around a fixation point. This is difficult because the mechanism to rotate the camera has to be small enough to be fitted inside the laparoscope, and the camera's centre of rotation (the fixation point) is located in front of the laparoscope (Ch. 7). In addition it was found that the laparoscope is better not held by an assistant when the surgeon is performing a manipulation task (Ch. 6). Instead, the laparoscope should rather be mounted in a mechanical support. Both requirements, allowing the surgeon control over his point of observation and mounting the laparoscope, were combined in the final prototype (Ch. 7). This final prototype, based on a circular guide, is shown in Fig. 8.1. Compared to the previous prototypes, for example that with a movable tip or a movable camera inside the tip, the circular guide has two advantages: first, all mechanical parts are located outside the abdomen, reducing the limitations on technical implementation, and second, this solution does not require a special optical device and can therefore be used with a common laparoscope.

The circular guide places the control over the laparoscope where it belongs, namely, with the surgeon. This restores the coupling between perception and action and allows the surgeon to explore his working area.

Figure 8.1
The Circular Guide.

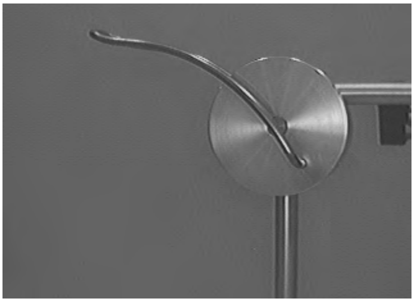


Figure 8.2
The mounting device, which can be operated to readjust the orientation of the circular guide using only one hand for releasing and locking.

From the surgeon's point of view, having control over the explorative movements of the laparoscope creates a new problem. As there is no assistant to hold and redirect the laparoscope the surgeon has to redirect the laparoscope himself. Redirections in the horizontal plane can be performed directly on the laparoscope. However, redirections in the vertical plane also require the change of the orientation of the circular guide. For this reason a mounting device was designed that allows the surgeon to adjust the orientation of the circular guide (Fig. 8.2). This mounting device was designed such that it can be manipulated with one hand, leaving the other hand free for redirecting the laparoscope.

The circular guide and the mounting device were evaluated in a practical setting by a surgeon performing a manipulation task. The circular guide was found to function well and the surgeon was enthusiastic about the control obtained over his visual information. The mounting device, however, did not work as well as anticipated. The surgeon performed all adjustments on the laparoscope, and did not use the mounting device for redirecting the laparoscope. Reducing the grip of the mounting on the circular guide solved this problem. Overall, the surgeon was able to perform the operation without assistance.

8.3 Future implementation

With respect to implementing perception-action coupling a number of questions remain:

- A more complete evaluation study of the circular guide in a practical setting is recommended. In the thesis an evaluation was done with one surgeon. For further development a larger evaluation study is needed, preferably in a practical setting. This might, for example, be performed within the newly started MISIT[1] program.

- Research into the feasibility of a link between the laparoscope and head movements in other than the horizontal direction is recommended. Currently the link between the laparoscope and the head movements of the surgeon is implemented only for the horizontal direction. The result of Exp. 1 (Ch. 4) showed that movements in another than the horizontal direction are not used when performing an exploration task. However, when the movements of the laparoscope in the horizontal direction are linked to the head movements, then the surgeon automatically tries moving the laparoscope in the other directions, and is consequently inclined to suggest that such an implementation may be an advantage. This will have to be tested with a feasibility study in a practical situation.
- Research into the redesign of laparoscopic instruments is recommended. Precise manipulation restricts the surgeon from making head movements. Current laparoscopic instruments are designed in such a way that they restrict the surgeon's movements. For example, the design of the grip is such that the surgeon is virtually unable to use his wrist. Such restrictions affect the overall movements of the surgeon, and thus also the amount of exploration he can do. The design of instruments which do not force specific action on the surgeon may allow for exploration during manipulation.
- Research into separating the movements of the camera from the movements of the light source is recommended. The results of Exp. 2 showed the importance of decoupling the camera and the light source. The advantage of this was also indicated by the results of Exp. 5. Shadow parallax was proposed for decoupling the camera and light source. However, the evaluation at the Academic Medical Centre of the University of Amsterdam (AMC/UvA, Ch. 7) showed that the variation in light intensity created by shadow parallax was too subtle. Future implementation may investigate different methods for decoupling camera and light source.
- Research into the quantification of affordances is recommended. For example, the DVWS is suitable for tasks that invite the observer to move. However, observer movements are affected not only by the task, but also by the environment in which the task must be performed (Ch. 2). Analysis of the influence of the environment on the observer action points to a need to quantify and analyse observer behaviour with respect to the task that is performed (controlled actions) and how this task is performed (control actions).
- A redesign of the circular guide is recommended. The circular guide, as described in Chapter 7, is a technical solution and demonstrates technical functionality. For it to make the step from a prototype to a real product, it needs a designer's touch.

The research described here has used the direct perception theory as framework for implementation. The advantage of using the direct perception theory as framework is that it invites to test ideas when they are still in a ‘wood and wire’ stage, and that it forces to focus on the interaction between task and action possibilities. As a result, implementation focuses on affordances.

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[1] Minimally Invasive Surgery and Intervention Techniques: an interdisciplinary research project of the Delft University of Technology, which aims at alleviating the limitations introduced by the present technology of minimally invasive procedures.

APPENDIX I

DVWS

The Delft Virtual Window System

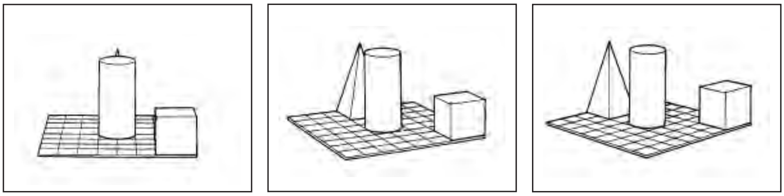


Figure A1.1 *Successive views of three objects for an observer who moves from the centre to the left.*

A1.0 Theoretical considerations

During observer movements, objects appear to shift within the viewing area. These apparent shifts are called movement parallax. Movement parallax depends on the observer's movement relative to the object. For example, Figure A1.1 gives successive views when the observer makes a circular movement around three objects, a pyramid, a cube and, at the fixation point, a cylinder. Two facts can be noticed. First, as the observer moves from the centre to the left, the pyramid, which is behind the fixation point, appears to shift with the observer whereas the cube, which is in front of the fixation point, appears to move opposite to the observer. Second, the amount of the shift depends on distance from the fixation point. The relation between parallax shifts and observer movements is illustrated in Figure A1.2.

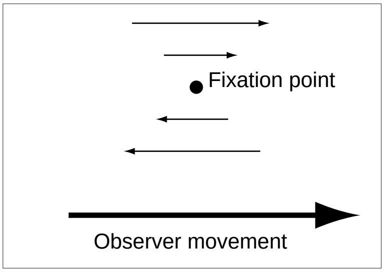


Figure A1.2
Parallax shifts when moving around a fixation point.

A1.1 Technical implementation

Shifts similar to movement parallax can be generated within an image by rotating a camera around a fixation point while it is aimed at this point. Then, objects behind the fixation point appear to shift within the image in the same direction as the camera and objects in front of the fixation point appear to shift within the image in the opposite direction to the camera. Such camera motions therefore provide spatial information about the scene observed.

If the movements of the camera are linked to the movements of the observer, the observer is able to relate the shifts within the image to his own movements. This allows him not only to obtain spatial information about the scene observed, but also to relate the spatial layout to his own movements,

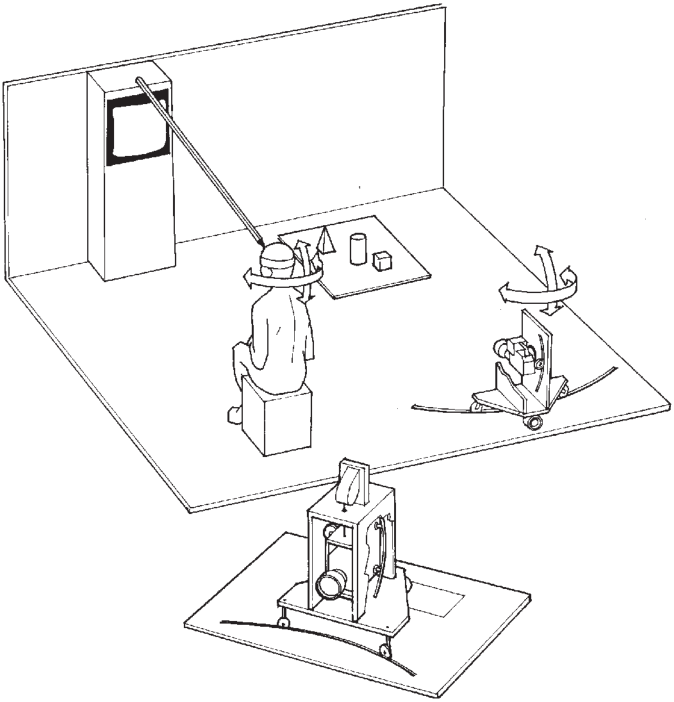


Figure A1.3
Experimental set-up used by Overbeeke [Overbeeke et al. 1988].

and hence to his own body. This technical implementation, where the camera rotates around a fixation point and the motions of this camera are linked to the movements of the observer, is called the Delft Virtual Window System [DVWS, Smets 1995, Overbeeke *et al.* 1988]. Figure A1.3 shows one of the experimental set-ups used.

A1.2 Original recommendations

Based on experiments with the DVWS the following three remarks can be made with respect to implementation [Overbeeke *et al.* 1988]. First, the direct link between observer movements and the corresponding shifts in the scene is of fundamental importance to the system. The camera that picks up the image must be present at all times so that the monitor will instantaneously show the image corresponding to the observer's position. Second, the fixation point is the link between observer movements and the shifts in the scene. It is precisely for this reason that the observer perceives the scene as stable, and it is only then that a convincing impression can be achieved. Third, the new system offers advantages because it involves the observer in what he observes.

In conclusion, although the technical set-up used by Overbeeke *et al.* [1988] had some failings, and although their experiments were conducted with a primitive set-up, with few subjects, and were analysed using crude statistical tests, the results of the experiments were found to be statistically significant and did show that the system works.

APPENDIX II

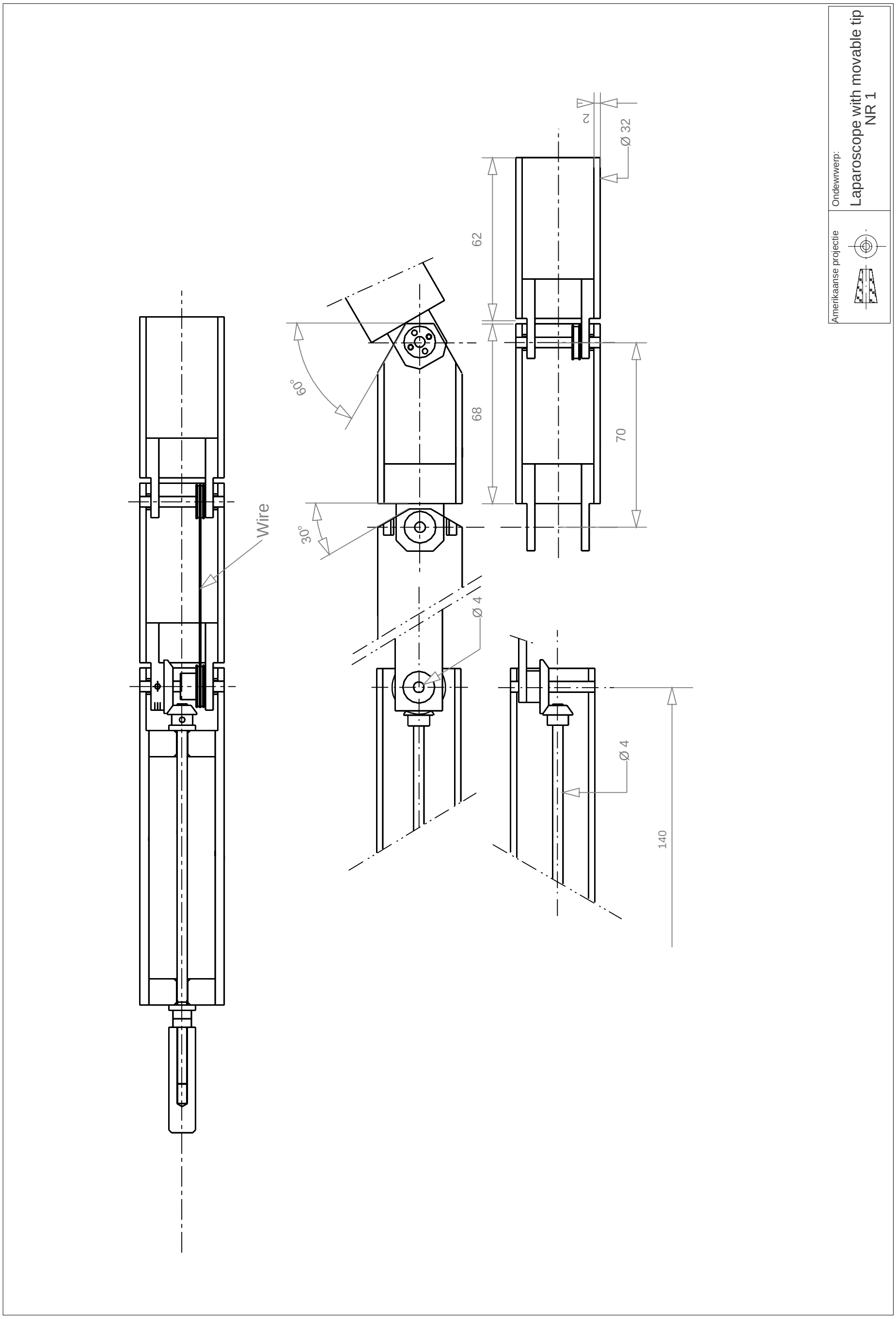
TECHNICAL DRAWINGS

Overview:

A:	A laparoscope with a movable tip [Prototype II]
B:	A laparoscope with a movable tip and a relocatable point of rotation [Prototype III]
C:	A borescope based on shadow parallax [Prototype V]
D:	The circular guide [final prototype]
E:	The mounting device [final prototype]

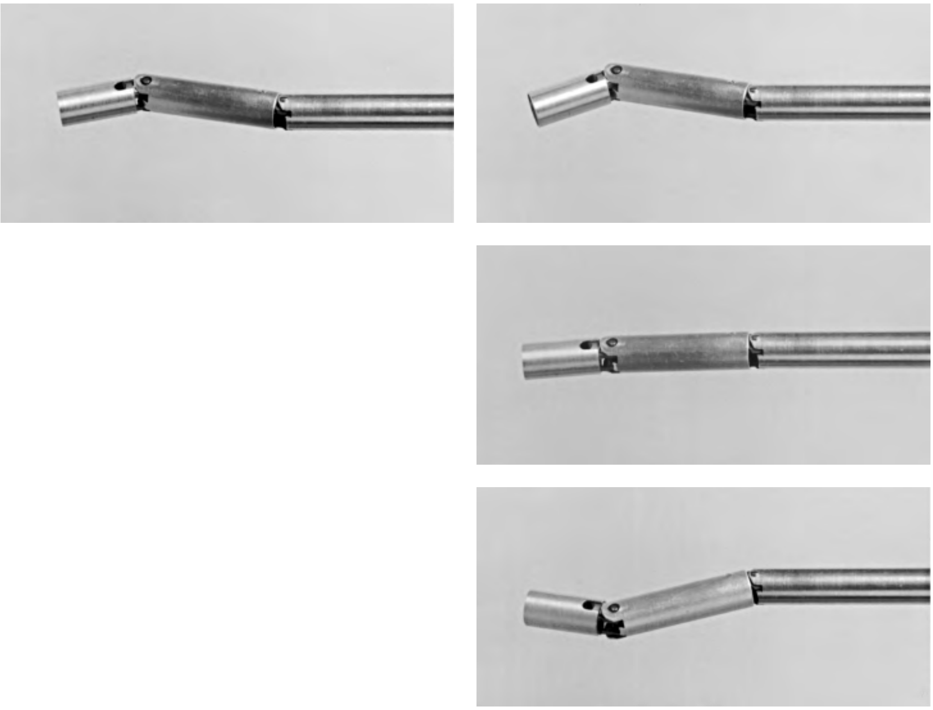
A

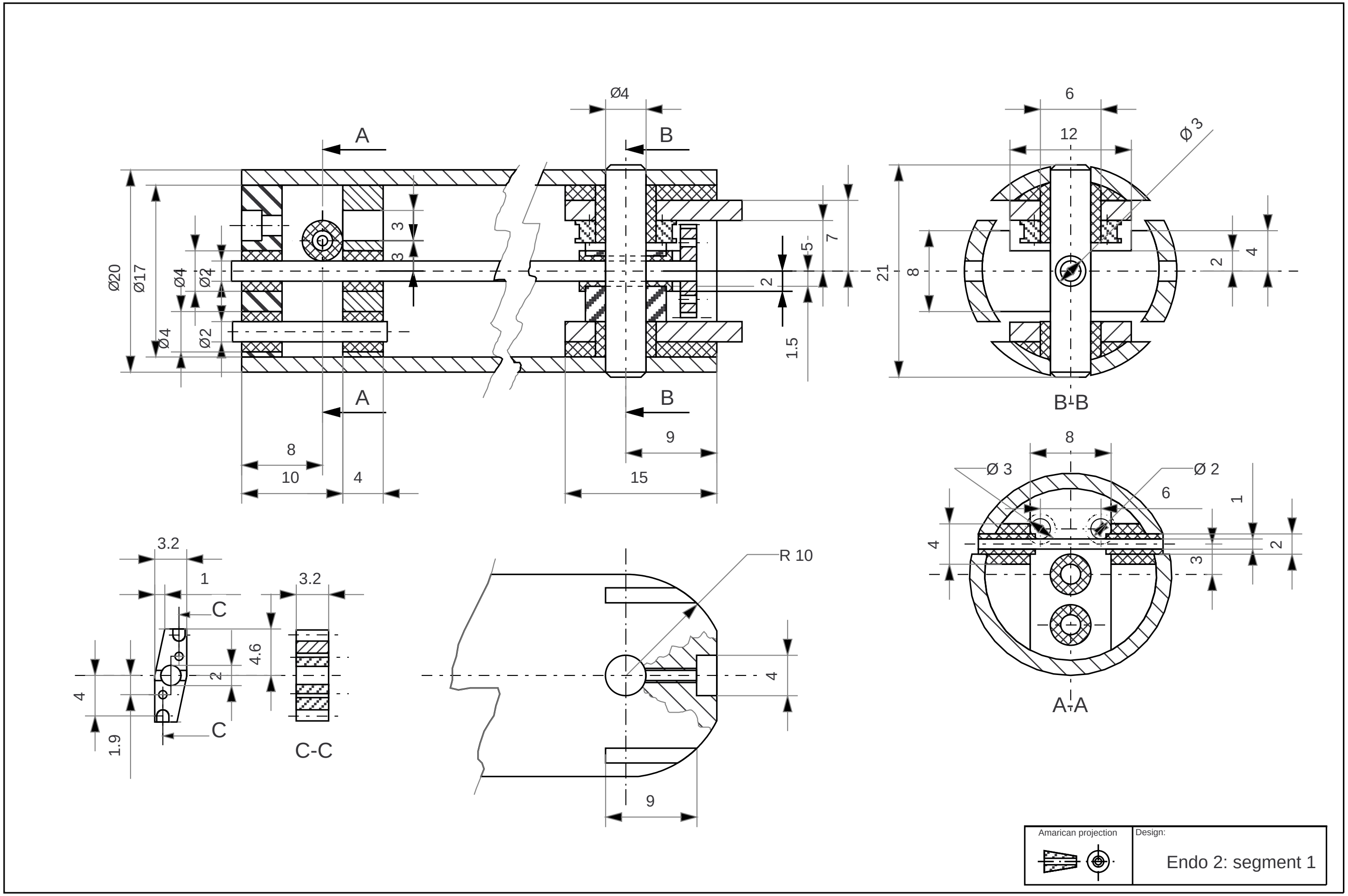
Technical drawings of prototype II

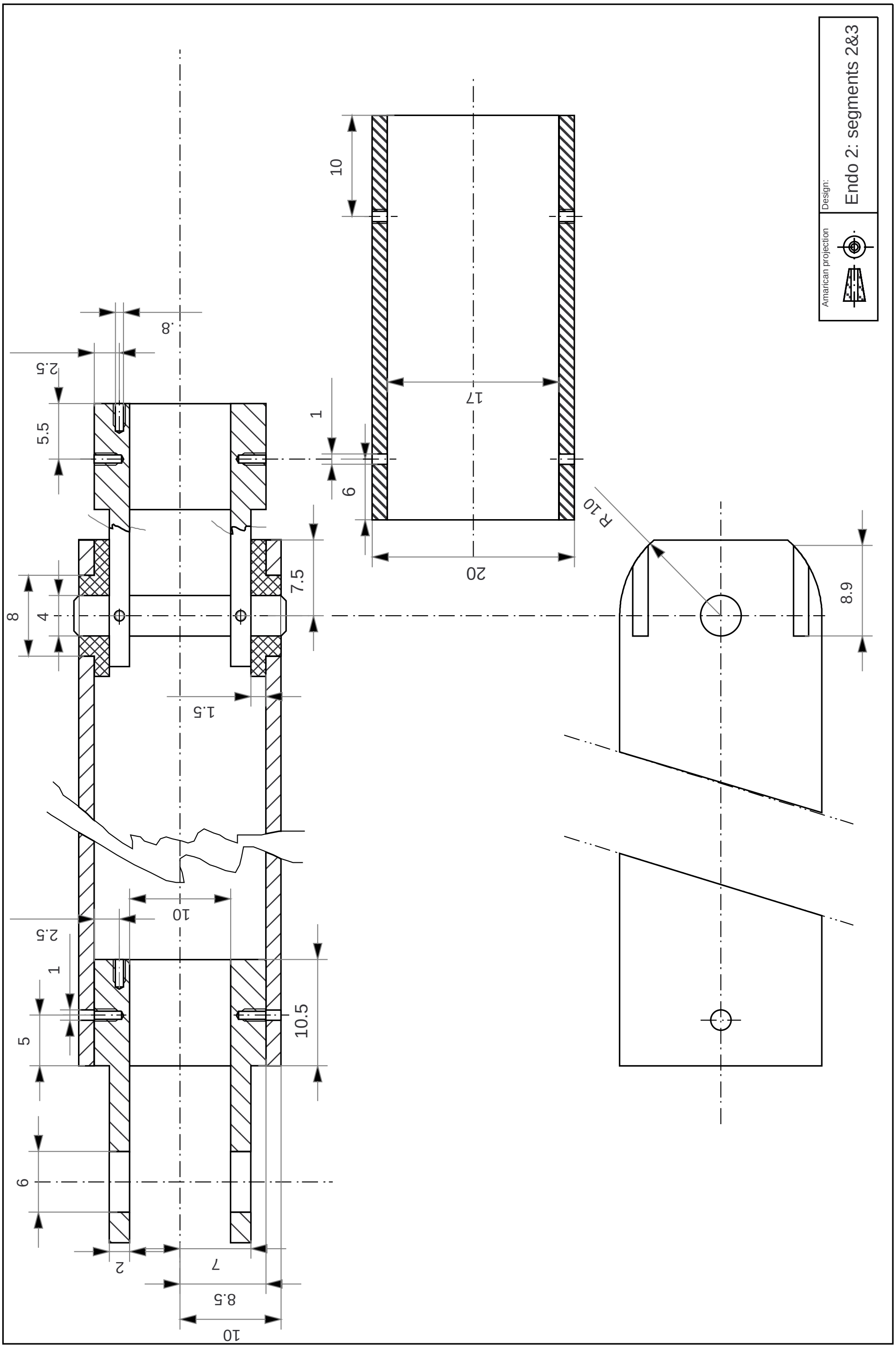

Ondewrwerp:
Laparoscope with movable tip
NR 1
Amerikaanse projectie
2
Ø 32
62
68
70
60°
30°
Wire
Ø 4
Ø 4
140

B

Technical drawings of Prototype III

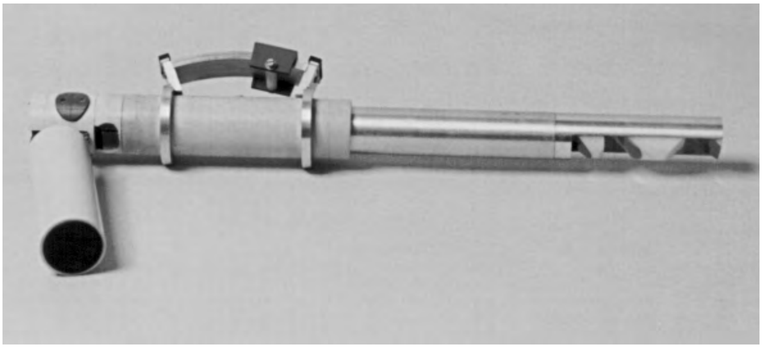


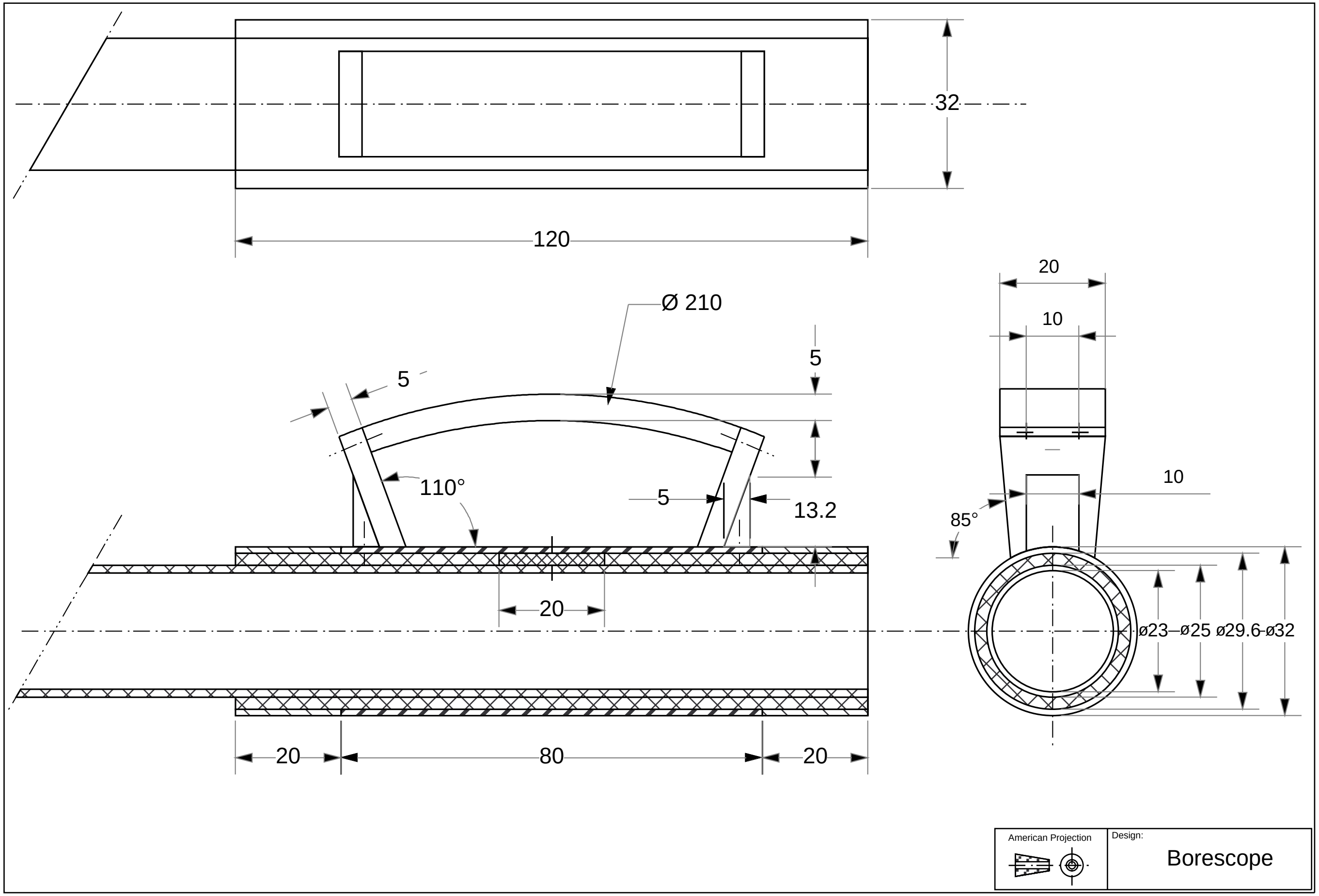

Ø4
A
B
6
12
Ø 3
Ø20
Ø17
Ø4
Ø2
Ø4
Ø2
3
3
5
7
2
1.5
21
8
2
4
B-B
A
B
8
10
4
9
15
8
Ø 3
Ø 2
6
1
4
2
3
A-A
3.2
1
C
3.2
4.6
2
4
1.9
C
C-C
R 10
4
9
Amarican projection
Design:
Endo 2: segment 1

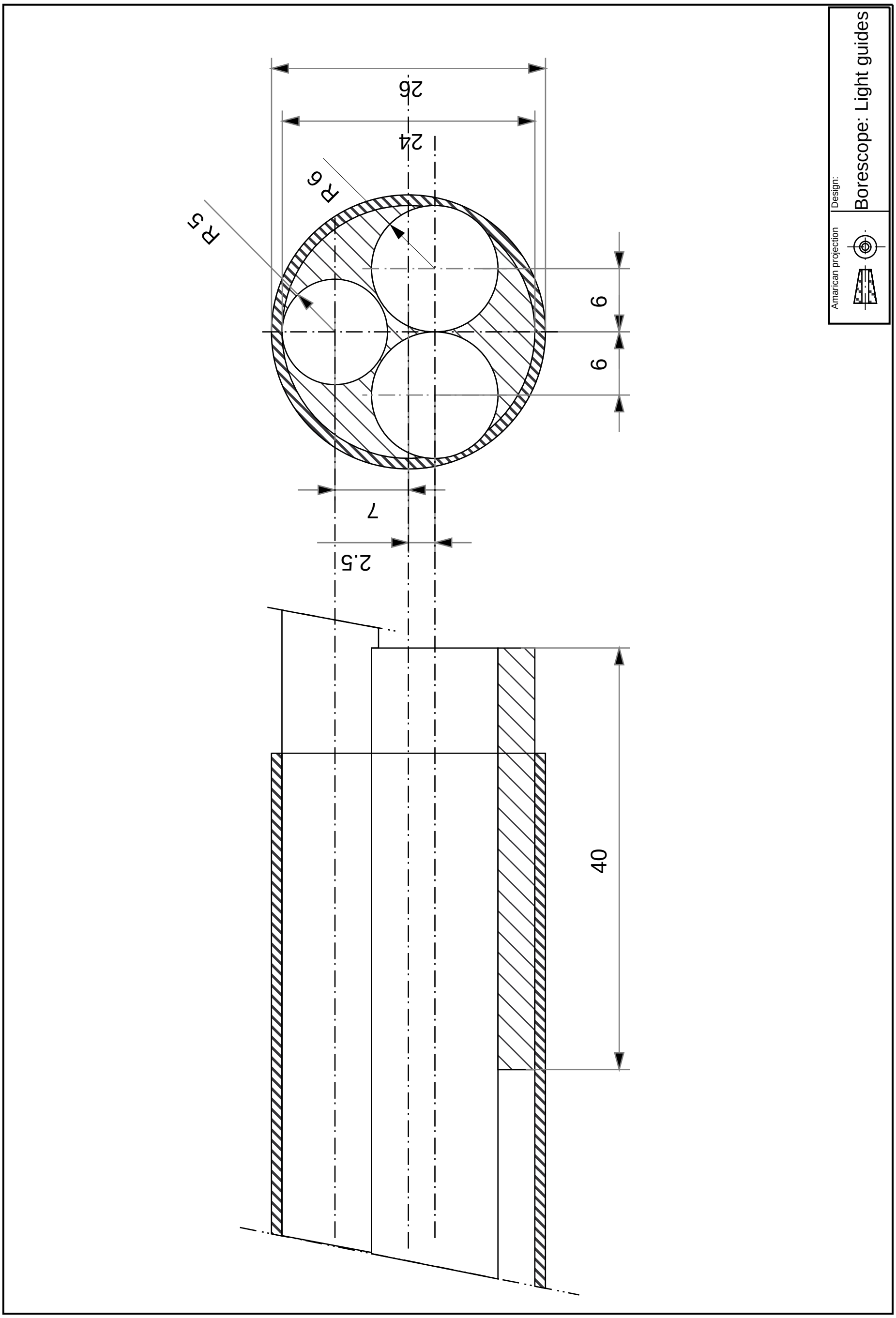

Amarican projection
Design:
Endo 2: segments 2&3
10
1
6
17
20
R 10
8.9
.8
2.5
5.5
8
4
7.5
1.5
10
2.5
1
5
10.5
6
2
7
8.5
10

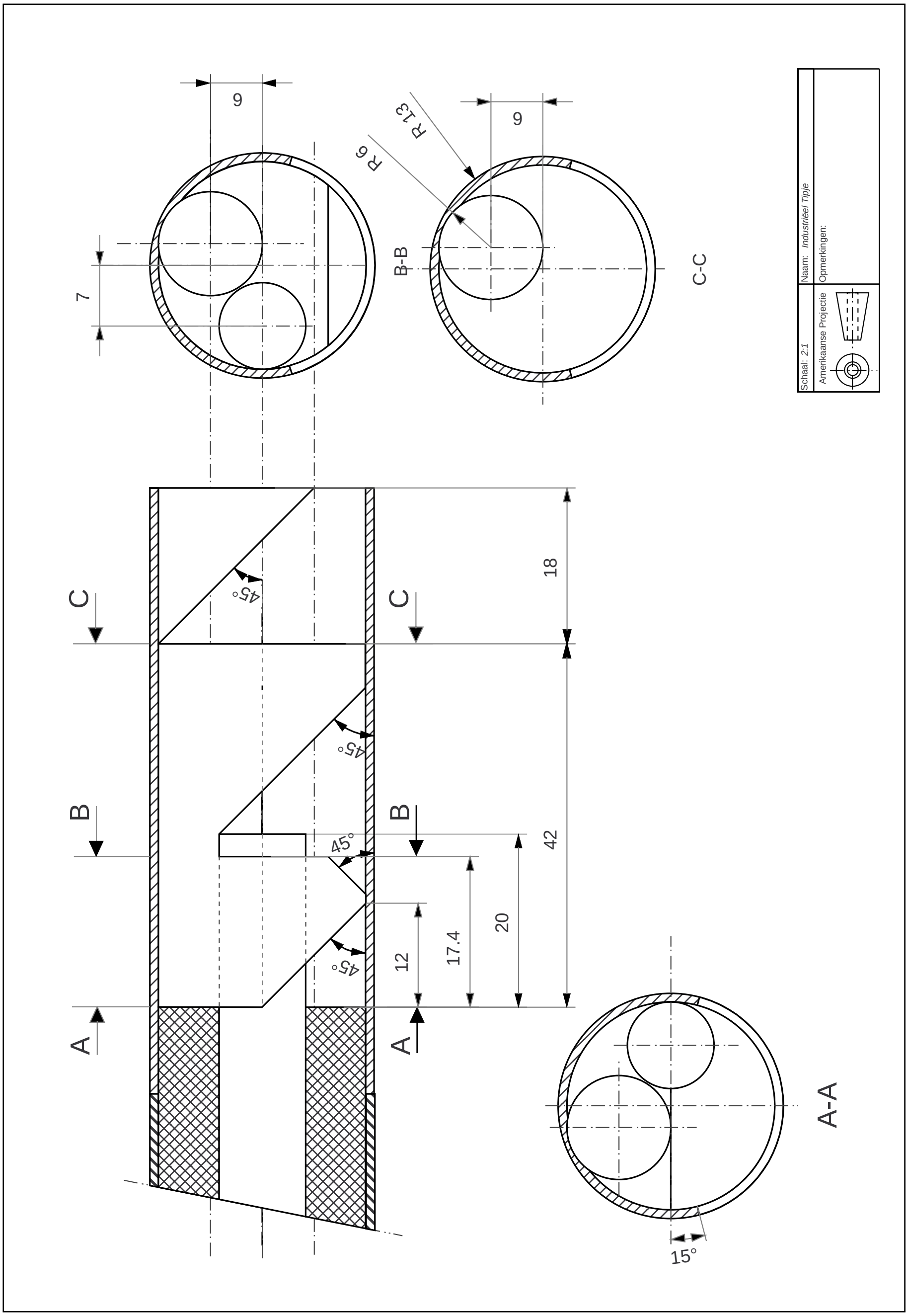
C

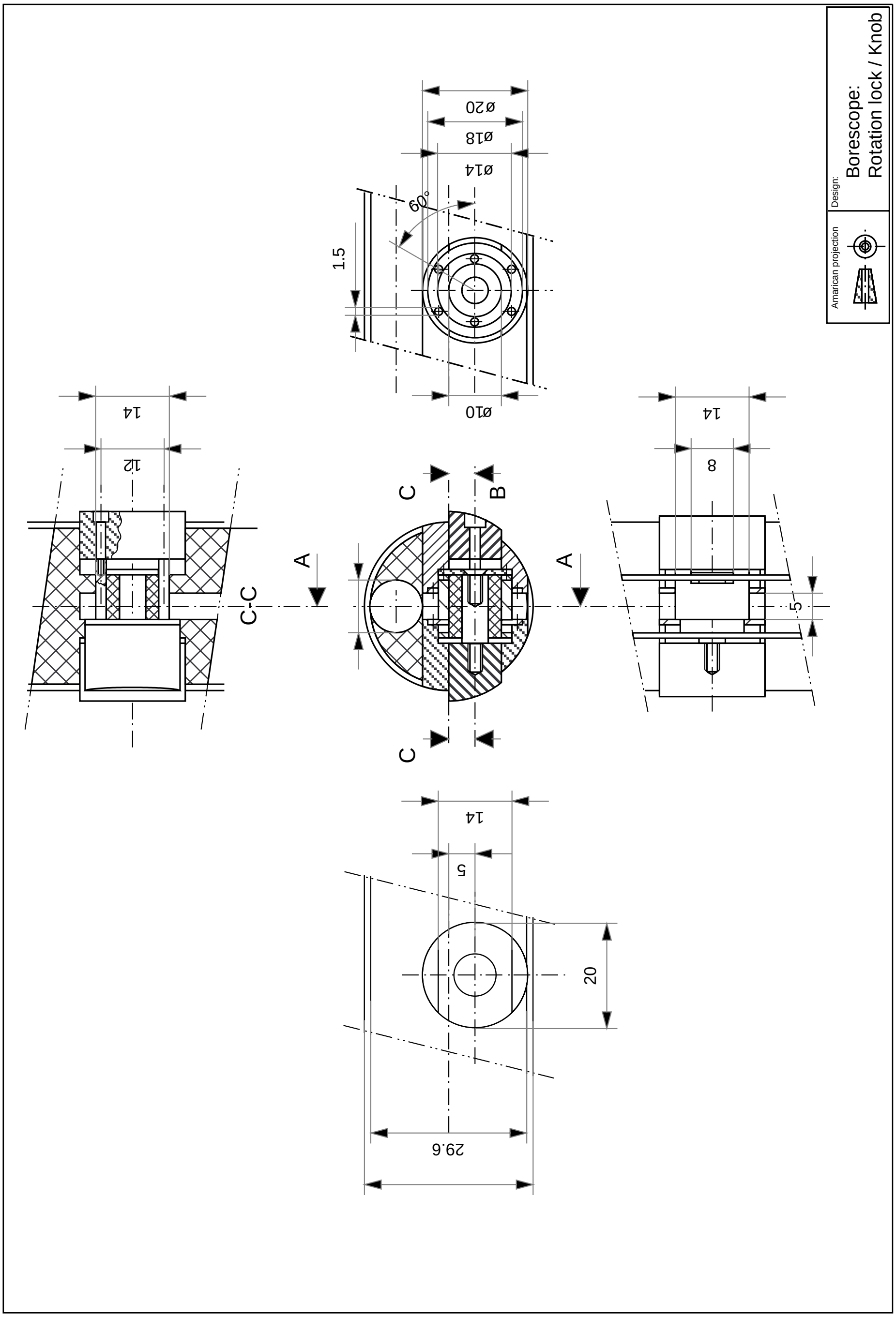
Technical drawings of prototype V




32
120
Ø 210
5
5
110°
5
13.2
20
20
80
20
20
10
10
85°
ø23
ø25
ø29.6
ø32
American Projection
Design:
Borescope


26
24
R 6
R 5
6
6
7
2.5
40
Amarican projection
Design:
Borescope: Light guides

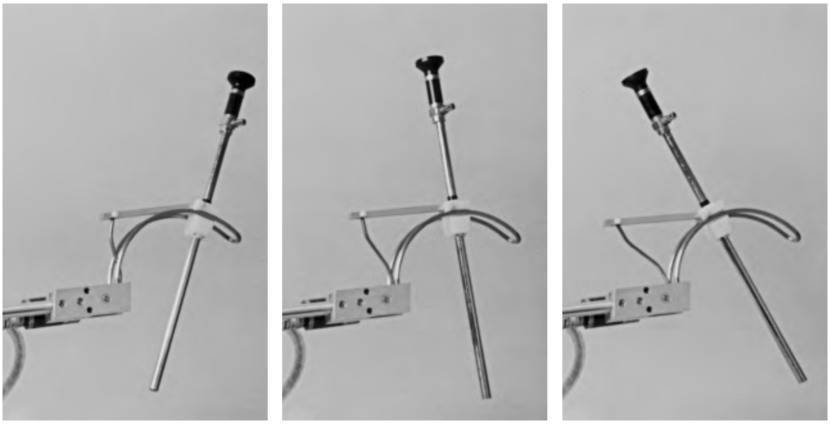

9
9
R 6
R 13
7
B-B
C-C
C
C
45°
45°
45°
45°
B
B
A
A
18
42
20
17.4
12
A-A
15°
Schaal: 2:1
Naam: Industriëel Tipje
Amerikaanse Projectie
Opmerkingen:

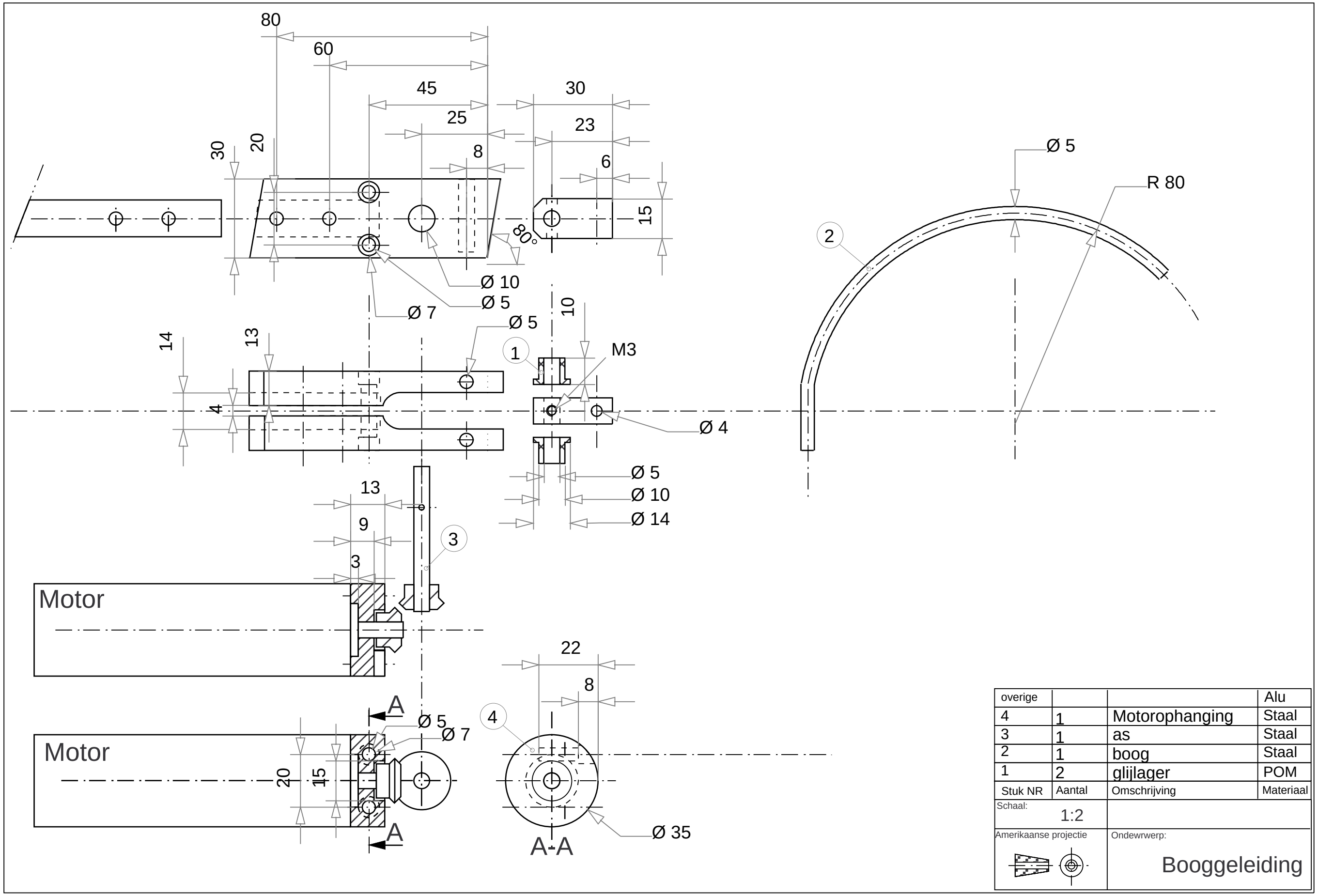

Amarican projection
Design:
Borescope:
Rotation lock / Knob
ø20
ø18
ø14
60°
1.5
ø10
14
12
14
8
C
B
A
C-C
A
5
C
14
5
20
29.6

D

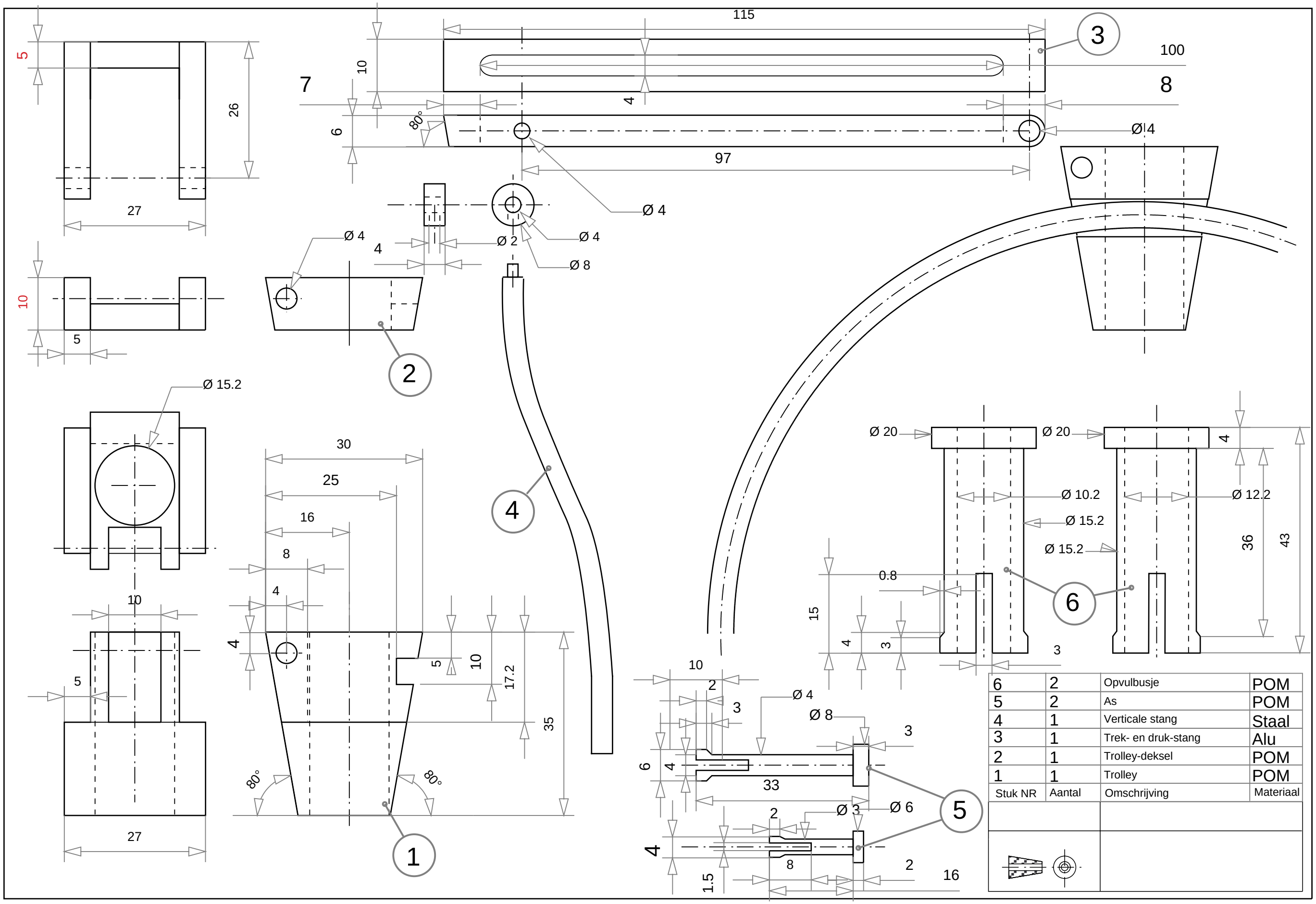
THE CIRCULAR GUIDE

Technical drawings of the final prototype





overige			Alu
4	1	Motorophanging	Staal
3	1	as	Staal
2	1	boog	Staal
1	2	glijlager	POM
Stuk NR	Aantal	Omschrijving	Materiaal
Schaal: 1:2			
Amerikaanse projectie		Ondewrwerp: Booggeleiding	

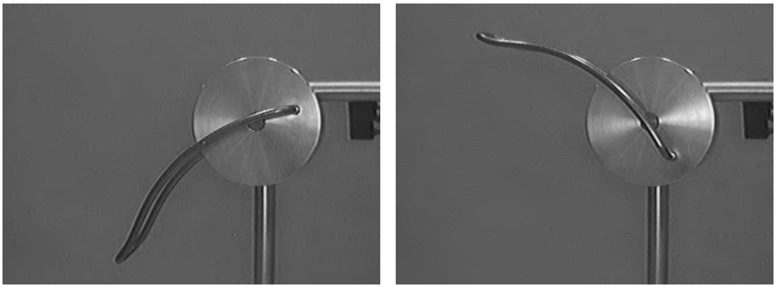


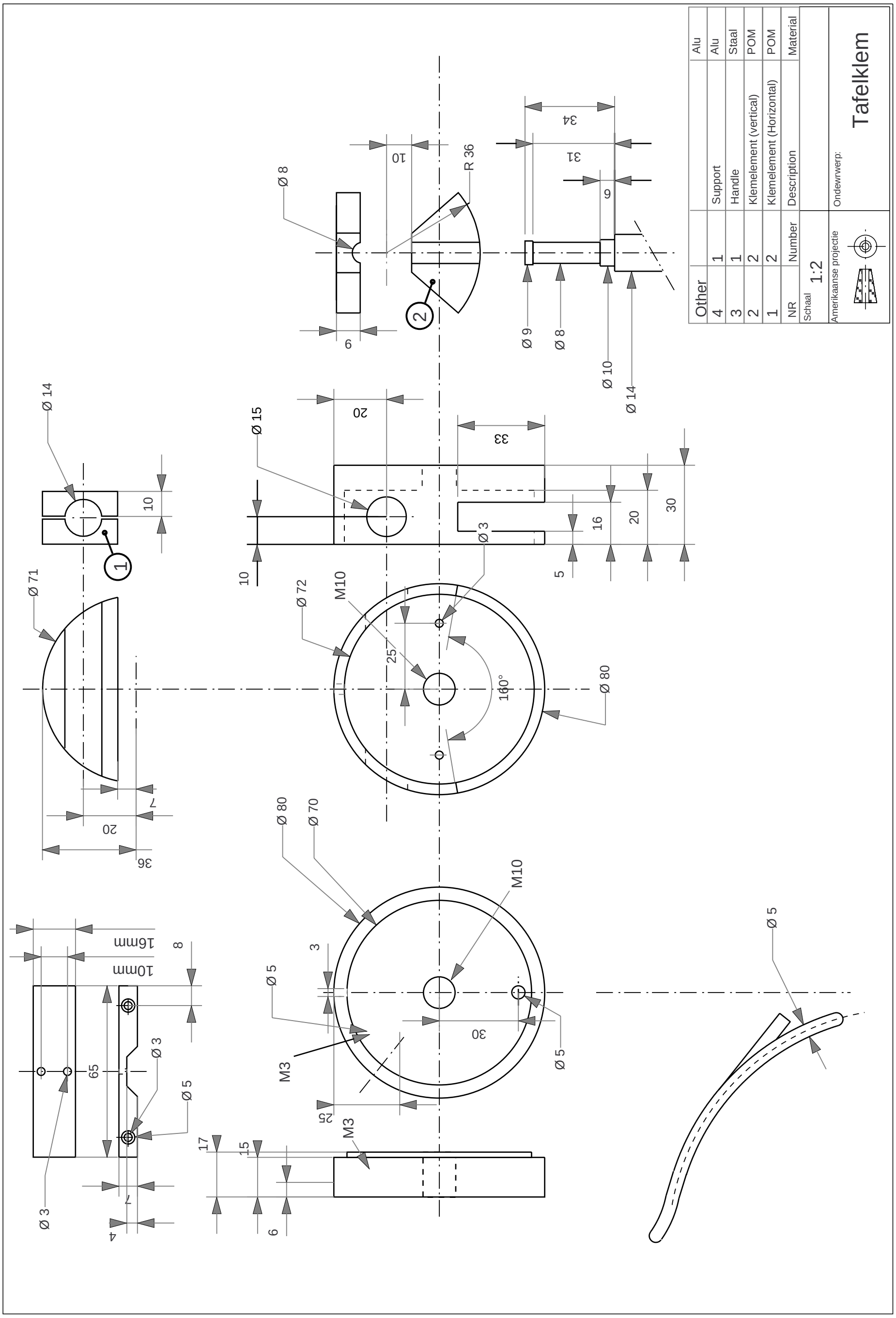
Stuk NR	Aantal	Omschrijving	Materiaal
6	2	Opvulbusje	POM
5	2	As	POM
4	1	Verticale stang	Staal
3	1	Trek- en druk-stang	Alu
2	1	Trolley-deksel	POM
1	1	Trolley	POM

E

THE MOUNTING DEVICE

Technical drawings of the final prototype




Tafelklem
Ondewrwerp:
Schaal 1:2
Amerikaanse projectie
NR
Number
Description
Material
Other
Alu
4
1
Support
Alu
3
1
Handle
Staal
2
2
Klemelement (vertical)
POM
1
2
Klemelement (Horizontal)
POM
1
2
Ø 14
10
Ø 71
20
36
7
16mm
10mm
8
65
Ø 3
Ø 5
7
4
Ø 3
17
15
6
Ø 15
20
10
33
16
20
30
5
Ø 3
Ø 72
M10
25
160°
Ø 80
Ø 80
Ø 70
Ø 5
3
M3
M10
30
Ø 5
25
M3
Ø 8
10
R 36
6
34
31
6
Ø 9
Ø 8
Ø 10
Ø 14
Ø 5

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AFFORDING ACTION

Implementing Perception-Action coupling for Endoscopy

F.A. Voorhorst

This thesis describes a study which investigates the possibility of implementing the Delft Virtual Window System [DVWS, App. I, Smets 1995b, Overbeeke *et al.* 1988]. The DVWS is a technical implementation of viewpoint parallax. It provides spatial information by linking the motions of a camera to the head movements of the observer. The observer controlling the camera obtains spatial information about the object displayed on the monitor. Moreover, he can relate the object's size to his own movements and thus to himself. Spatial information is obtained by coupling perception and action.

The aim this research is the implementation of the DVWS for laparoscopy. Laparoscopy is a minimal invasive surgical technique during which the patient is treated through small ‘key-holes’ (trocars) in the abdomen wall. For obtaining visual information a laparoscope is used, which is basically a tube with a built-in lens system for observation, and with built-in light guides for illumination. On the outer end of the laparoscope a camera is mounted, the image from which is presented on a monitor. Spatial information is limited for a number of reasons. For example, laparoscopes have an integrated light source, which reduces the visibility of shading and therefore flattens the image. Also, the laparoscope is not held or directed by the surgeon, because he needs both hands to operate, but by an assistant. Implementing the DVWS will restore the surgeon's direct control over the laparoscope and allow him to obtain spatial information through exploration. What kind of information is needed depends on the task to be performed.

Laparoscopy consists of two types of tasks (Ch. 3); observation and manipulation tasks. Both types differ in the spatial information they require. Observation tasks require the perception of the spatial structure, for example, to identify the various tissues. Manipulation tasks, however, also require the perception of how the layout is related to the observer. This is needed, for example, to move from one location to another. The information needed for both tasks (about the spatial layout and about how this layout is related to the surgeon) can be obtained through explorative movements.

For both tasks an implementation of the DVWS seems feasible. However, two major problems arise. First, the feasibility of the DVWS depends on whether or not the surgeon will move. Whereas observation tasks invite movements, manipulation tasks do not (Ch. 4). For example, when manipulation requires a high degree of manual stability, the surgeon will sit as still as possible. However, when little hand stability is required, it is found that the ability to explore can be an advantage (Ch. 6). Moreover, the assistant holding the laparoscope was found to influence the surgeon's performance of a manipulation task. An implementation of the DVWS should also support the laparoscope.

Secondly, implementing the DVWS (viewpoint parallax) is technically complex, and therefore balances between perceptual criteria (what kind of information has to be provided) and technical criteria (what kind of information can be provided). A simpler technical implementation is shadow parallax, i.e., the motions of the light source are linked to the movements of the observer (Ch. 5). Shadow parallax provides similar perceptual information (variation in shading and shifting shadows) but has the advantage that a moving light source can be implemented by two stationary light sources of which the intensity balance varies. Its implementation thus only requires two separate light guides. Shadow parallax was found to be applicable for detecting differences in heights (industrial application, Ch. 5) but, it was found to provide insufficient information for application for laparoscopy (Ch. 6). For laparoscopy, viewpoint parallax has the advantage.

To arrive at a simple technical implementation of viewpoint parallax, the large viewing angle (fish eye) that laparoscopes commonly have was made use of. This fish-eye makes it possible to direct the laparoscope away from the area of interest, while maintaining the area within vision. Directing the laparoscope will translate the tip of the laparoscope and, as a result, the area of interest is will be observed from a different point of observation

The DVWS was implemented into a working prototype, the Circular Guide (Ch. 7). The Circular Guide links the head movements of the surgeon to the rotation of the laparoscope around the point where it enters the abdomen. The Circular Guide can be used in combination with a common laparoscope. It was designed such that the surgeon can easily control his point of observation either through head movements or manually. Additionally, a mounting device was designed to simplify (re-) installing the Circular Guide.

Both the Circular Guide and the mounting device were tried in a practical setting. They allowed the surgeon to perform an operation without needing assistance for the manipulation of the laparoscope. The circular guide was found to work properly, but the mounting device was found to need some adjustments. Overall, the surgeon was enthusiastic about the regained control over his visual information.

GELEGENHEID TOT EXPLOREREN

Implementatie van Perceptie-Actie koppeling voor Endoscopie

F.A. Voorhorst

In deze dissertatie wordt de implementatie beschreven van het Delft Virtual Window System [DVWS, App. I, Smets 1995, Overbeeke *et al.* 1988]. Het DVWS is een technische implementatie van viewpointparallax. Het geeft ruimtelijke informatie via een monitor door de hoofdbewegingen van de waarnemer te koppelen aan de bewegingen van de camera. Ruimtelijke informatie volgt uit het feit dat perceptie en actie gekoppeld zijn.

Het doel van dit onderzoek is de implementatie van het DVWS voor laparoscopie. Laparoscopie is een minimaal invasieve chirurgische ingreep in de buikholte waarbij de patiënt wordt geopereerd door kleine 'sleutelgaten' (trocars). Visuele informatie wordt verkregen met een laparoscoop, een soort van buis is met een lenzensysteem voor het beeld en met glasfibers voor de verlichting. Op de laparoscoop wordt een camera geplaatst waarvan het beeld wordt getoond op een monitor. In vergelijking met een conventionele operatie Zijn er twee grote verschillen. Ten eerste heeft de chirurg minder ruimtelijke informatie, bijvoorbeeld, omdat laparoscopen monoculair zijn. Tevens zijn zowel optiek als lichtbron geïntegreerd in één apparaat. De hierdoor gereduceerde schaduw maakt het beeld plat. Ten tweede heeft de chirurg geen directe controle over de laparoscoop, aangezien hij beide handen nodig heeft om te opereren. De laparoscoop wordt vastgehouden door een assistent. Implementatie van het DVWS lost beide problemen op: de chirurg krijgt ruimtelijke informatie door te bewegen, en hij krijgt de controle over de laparoscoop terug. Welke informatie nodig is, en dus welke informatie moet worden aangeboden, hangt af van de taak wordt uitgevoerd.

Tijdens laparoscopie zijn er grofweg twee taken: observatie en manipulatie (H 3). Beide verschillen in de ruimtelijke informatie die ervoor nodig is. Voor observatietaken is het voldoende om de ruimtelijke struktuur te kunnen waarnemen, bijvoorbeeld om weefsel te kunnen identificeren. Voor manipulatietaken zal de ruimtelijke structuur ook gerelateerd moeten zijn aan het standpunt van de waarnemer, bijvoorbeeld om van het ene punt naar het andere te kunnen bewegen. Herstellen van de koppeling tussen perceptie en actie maakt dat de ruimtelijke structuur gerelateerd is aan de bewegingen van de waarnemer, en dus aan de waarnemer zelf.

Voor beide taken lijkt een implementatie van het DVWS zinvol. Er zijn echter twee problemen. Ten eerste vereist het DVWS dat de chirurg zal bewegen. Dit zal tijdens observatie wel het geval zijn. maar in mindere mate tijdens manipulatie. Afhankelijk van de complexiteit van de manipulatie zal de chirurg meer of minder bewegen. Het voordeel van het DVWS voor manipulatie taken is ook afhankelijk van het feit of een assistent de laparoscoop vast houdt of dat deze mechanisch wordt ondersteund. Experimenten hebben aangetoond dat het laatste de voorkeur heeft.

Een tweede probleem voor de implementatie is dat voor het genereren van de vereiste camerabewegingen een complex mechanisme nodig is. Daarom zal bij implementatie een afweging gemaakt moeten worden tussen de informatie die nodig is voor het uitvoeren van de taak (perceptuele criteria) en de informatie kan worden aangeboden (technische criteria). Een alternatieve informatiebron waarbij geen bewegende delen in de laparoscoop nodig zijn is schaduwparallax: hierbij zijn de hoofdbewegingen van de waarnemer gekoppeld aan de bewegingen van de lichtbron. Dit principe heeft als voordeel dat implementatie zeer eenvoudig is wanneer een bewegende lichtbron gesimuleerd wordt met twee stilstaande lichtbronnen waarvan de intensiteit varieert. Implementatie omvat dan slechts twee gescheiden lichtbronnen. Hoewel schaduwparallax toepasbaar is voor het onderscheiden van hoogteverschillen in een oppervlak, bleek het onvoldoende informatie te geven tijdens laparoscopie. Hiervoor heeft viewpointparallax de voorkeur.

Om viewpointparallax op een simpele manier te implementeren is gebruik gemaakt van de grote beeldhoek (fish-eye) van de laparoscoop. De fish-eye maakt het mogelijk om de laparoscoop van het werkgebied weg te draaien zonder dit gebied uit het zicht te verliezen. Dit wegdraaien heeft echter ook tot gevolg dat de het punt van waarneming (de tip van de laparoscoop) is verplaatst. Effectief wordt het gebied van interesse vanuit een ander standpunt bekeken, en dat is precies het gewenste effect. Deze methode van implementeren heeft dat slechts de laparoscoop geroteerd hoeft te worden.

Het onderzoek heeft geresulteerd in een werkend prototype, de Circular Guide (H 7). Deze wordt over de buikholte wordt geplaatst, en koppelt de rotatie van de laparoscoop rond het punt waar deze de buikwand binnengaat aan de hoofdbewegingen van de chirurg. Het prototype is zo ontworpen dat de chirurg de laparoscoop, door middel van hoofdbewegingen of handmatig, eenvoudig kan bedienen zonder daarbij assistentie nodig te hebben. Hiervoor is ook een klem ontworpen, die het de chirurg makkelijk maakt de Circular Guide te (her) installeren.

De Circular Guide en de klem zijn in een praktische opstelling geprobeerd. Hieruit bleek dat de Circular Guide werkte zoals verwacht, maar dat de klem nog enige aanpassing behoefde. De chirurg die de test uitvoerde was enthousiast de bewegingen van de laparoscoop zelf te controleren.

CURRICULUM VITAE

Fred-Anton Voorhorst was born in Leiden on 20 March 1968. In 1985 he gruaduated from the HAVO, and in 1987 from the VWO, at the Fons Vitae Lyceum in Amsterdam. In the same year he started his study at the Faculty of Mechanical Engineering of the Delft University of Technology. The work which led him to receiving his engineer's degree in 1993 was carried out in the laboratory of Man-Machine-Systems directed by Prof.dr.ir. H.G. Stassen. From 1993 to 1998 he worked on his PhD research at the Faculty of Industrial Design Engineering, within the laboratory of Form Theory directed by Prof.dr. G.J.F. Smets and, after her departure, by Dr. C.J. Overbeeke. In the same period he was a member of the Research Advisory Committee (from 1994 to 1995), as representative of PhD-students, and a member on the Faculty Board (from 1995 to its abolition in 1997). Over the years he developed a special interest in ecology (in particular Apples and Citroëns).

TU Delft

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Thesis propositions for:

AFFORDING ACTION

Implementing Perception-Action coupling for Endoscopy

1. *Affordances* are investigated either at an information processing level, or at a physiological level. However, the most interesting for a designer is to what extend information and physiology are related *(Ch 2)*.
2. It is often forgotten that space is only meaningful to an observer who can move *(Ch. 3)*.
3. During manipulation there is a trade-off between hand movements and head movements *(Chs. 4 & 6)*.
4. Control over visual information is more important than how this control is implemented *(Ch. 5)*.
5. Perception and action can only be separated for the purpose of analysis (*Ch. 6*).
6. Design is the process of (re-)creating *affordances* *(Ch. 7)*.
7. Although a decision often is based on emotional criteria, its explanation always is rational.
8. Interface design often ignores that interaction includes feedback, whereas feedback could be used to the advantage of technical simplicity and user-friendliness.
9. Considering the number of cars on Dutch roads, the speed limit could be halved without a noticeable change in travel time.
10. How swift one can make a model depends on the time it takes for the glue to dry.
11. Internet decreases the size of the world and increases the distance between people.
12. Without mon ami, where am *i*?

Stellingen behorend bij:

GELEGENHEID TOT EXPLOREREN

Implementatie van Perceptie-Actie koppeling voor Endoscopie

1. *Affordances* worden onderzocht binnen de context van de informatieverwerking of binnen een fysiologische context. Echter, voor de ontwerper is het meest interessant hoe informatie en fysiologie zijn gerelateerd *(H.2)*.
2. Het wordt vaak vergeten dat ruimte slechts betekenisvol is voor een waarnemer die kan bewegen *(H. 3)*.
3. Tijdens manipulatie is er een afwegen tussen handbewegingen en hoofdbewegingen *(Hs. 4 & 6)*.
4. Controle over visuele informatie is belangrijker dan de manier waarop controle wordt geïmplementeerd *(H. 5)*.
5. Perceptie en actie kunnen slechts in de analyse gescheiden worden *(H. 6)*.
6. Ontwerpen is het (re-)creëren van *affordances* *(H. 7)*.
7. Hoewel beslissingen meestal gebaseerd zijn op emotionele criteria, is hun uitleg altijd rationeel.
8. Bij ontwerpen van interfaces wordt vaak vergeten dat interactie terugkoppeling bevat, terwijl handig gebruik van terugkoppeling juist kan leiden tot technische eenvoud en gebruikersvriendelijkheid.
9. Met de huidige autodichtheid kan de maximale snelheid op de Nederlandse wegen worden gehalveerd zonder noemenswaardige toename van de gemiddelde reistijd.
10. De snelheid van modelbouw zit in de droogtijd van de lijm.
11. Internet maakt de wereld klein en vergroot de afstand tussen mensen.
12. In mijn eendje kom ik overal, maar ben ik nergens.