PhD. Research Proposal

Video enhancement and analysis for video-guided surgery

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1 Introdcution

Nowadays, several diseases are diagnosed or treated using interventional techniques allowing the access to the patient internal anatomy. While conventional open sugery relies on cutting the skin and separating the underlying tissues to get a direct access to the surgical target, *minimally invasive surgery* (MIS) is performed through small incisions (usually 0.5 – 1.5 cm) in order to reduce the surgical trauma and morbidity.

The term *laparoscopic surgery* refers to MIS performed in the abdominal or pelvic cavities. In order to create a working volume through which surgical instruments can be inserted via ports, the abdomen is insufflated with a specific dose of gas. Since direct viewing of the surgical scene is not possible, an endoscopic camera (stereoscope) assists the surgeon's navigation by providing views of the anatomical structures and the surgical instruments.

During the last three decades, MIS has become a popular diagnostic and treatment tool and it is widely used in surgery procedures. This success is certainly a result of medical advances. However it is especially due to image/video processing evolution and the development of new technologies on robotics, visualisation, tracking and registration which led to an evolution of video guided interventions.

One of the main challenges that faced surgeons in the laparoscopic chirurgical training is to adapt their tasks to a two dimensional (2D) flat chirurgical field view. This lack of depth perception, beside the loss of tactile feedback, implies a relevant sensory loss for the surgeon and it has been proven by [1] that a three dimensional (3D) vision improves laparoscopic skills and work. Therefore 3D laparoscopic visual systems such as the *Da Vinci* Surgical System [2] (Intuitive Surgical, Sunnyvale, CA) and the *EndoSite 3Di* Digital Vision System [3] (Viking Systems, La Jolla, CA) have been developed.

This convergence to 3D visual systems introduced new issues related to image quality and made it possible to assist the surgeons by developing and integrating image processing automatic tasks. This project aims to make advances on video-guided surgery systems for endoscopic interventions. More specifically, the main goals related to our research program are hereby presented :

- **Endoscopic image and video enhancement** : improve the streoscopic video quality by analyzing and removing/correcting the different detected artifacts such as acquisition artefacts, specular reflection, noise, color mismatch, illumination variation, etc.

- **Features extraction for laparoscopic videos** : develop robust features extraction algorithms for natural landmarks-based organ surface reconstruction and registration.

- Evaluate the proposed algorithms ~~of the upper described research areas~~ and try to improve the video enhancement results, the feature points detection process and the quality of the reconstructed surface in order to optimize the registration. A comparative study of our results with the proposed conventional approaches will be also performed to validate our algorithms that will be integrated in the 3D slicer[1] software used in *The Intervention Centre* in Oslo.

Figure 1 presents the block diagram of the overall proposed system.

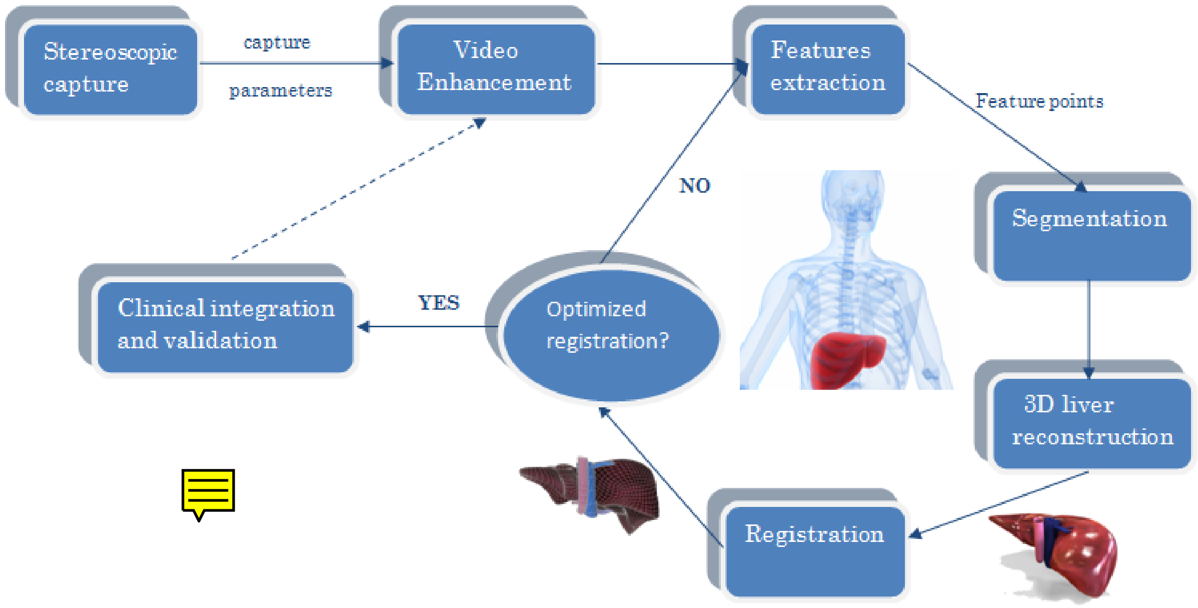

Figure 1: System overview

2 Background and research's direction

2.1 Endoscopic video enhancement

2.1.1 2D video enhancement

Video enhancement is one of the most important components for any application including a vision system where digital videos are acquired, processed and used. When it comes to a medical application domain, the challenge is greater since the video quality can affect the doctor's decisions and work, which can influence the patient health status.

The main goal is to improve the video visual appearance or to provide a better image transform representation for future automated video processing tasks such as analysis, segmentation, detection and recognition [4, 5, 6, 7] . Furthermore, it can help in understanding an object behavior by analyzing the background information and avoiding expensive human visual inspection [8], such as the case for the background moving organs in a surgical scene (due to the breathing process).

Although the great advances achieved in image processing, there is still no general standard or unifying theory that can be used as a video enhancement algorithm

[1] www.slicer.org

design criterion. However, based on the domain in which the images are processed, in the literature we distinguish two main approaches for video enhancement, namely spatial based domain and frequency based domain ~~video enhancement~~ [7, 9, 10, 6, 11]. While the first operates directly on image pixels, transform domain video enhancement techniques on the other hand manipulate the image transform coefficients which can be generated for exemple by discrete cosine transform (DCT), discrete wavelet transform (DWT) or Fourier transform.

Traditional video enhancement methods consist in improving low video quality using only local image information for each video frame (self-enhancement). These methods include contrast enhancement technique, wavelet-based video enhancement, compressed video enhancement and HDR video enhancement. On the other hand, new methods have been developed to enhance image quality by embedding information from a different time frame of the same video sequence. For instance, in order to adjust the luminance of a dark region, we can embed illumination information from a different time frame of the same video where this region is bright. Based on this idea, the authors of [12] classified video enhancement methods into two categories : Self-enhancement and Context based fusion enhancement.

2.1.2 3D video enhancement

Stereoscopic images/videos are used to improve the perception of depth and realism. Therefore, quality enhancement for stereo content is one of the most important techniques for any 3D-display system. Despite the increasing success of stereoscopic images, research on specialized image enhancement for 3D videos has been limited.

The simplest idea one could think about in the early ages of 3D image processing consists in enhancing independently each of the stereoscopic views using conventional 2D enhancement algorithms. However since the human visual system (HVS) does not perceive left and right images independently, a more integrated approach of cross-view image processing is better.

In [13], the authors take into account the HVS depth perception to propose a sharpness enhancement algorithm for 3D images. However, this solution neglects the luminance inter-difference between the left and the right views, which can produce eyestrain and visual fatigue.

Therefore several researches have been devoted to understand the HVS sensitivity for interview differences of stereo images, which opened the floor for the just noticeable difference (JND) concept. A JND model implies a visibility threshold for whish the HVS can detect changes in stimuli.

In [14], the authors control the sharpness enhancement using the Binocular-JND [15] model which refers to a visibility inter-difference threshold beyond which the HVS can recognize a changing. In [16], *Jung et al.* increase the depth difference between objects so that the differences exceed the Depth-JND value (JNDD) [17], so as to make them more visible. This should improve the 3D immersive experience and improve the depth feeling.

The foreground objects of the scene are supposed to be the most visible and have more defined contours. Moreover, moving objects are usually perceived more blurred than static ones. Based on these two assumptions, the authors of [18] enhance 3D videos by reducing the feeling of artificial clarity that can be experienced by the viewers [19].

2.1.3 Related artifacts and problems

As a matter of fact, endoscopic videos have quite special characteristics related to their content specifications (geometric characteristics of the endo-human organs, luminance, colors specification features of the tissues, etc.) and the capture/processing procedure (camera specifications and calibration, reduced and distorted field of view, display system, coding). Thus, endoscopic video enhancement algorithms have to deal with specific problems with respect to the included artifacts. In this paragraph, we list and focus on the possible artifacts and problems related to endoscopic video enhancement.

Specular reflections Specular reflections are considered as one of the major concerns in laparoscopic image enhancement and processing for two reasons. First because it is very frequent and present in the majority of laparoscopic interventions. Second because its suppression can affect all following processing tasks like organs segmentation, classification and registration which makes it a very important step in endoscopic image analysis. Due to moist tissue, specular reflections appear as white glare or light-colored glare (as shown in Fig. 2) and get brighter when the surface normal bisects the angle between the vision direction (camera) and the incident light.

Many approaches have been proposed to remove specular reflections in an endoscopic environment. Most of them (e.g [20, 21]), are based on the dichromatic reflectance model [22, 23] which is made for dielectric inhomogeneous materials and thus it is not suitable for biological material like human tissue. In [24], the authors show that a simple thresholding in the HSV color space can give a similar accuracy and performance on endoscopic images.

Therefore, the most recent proposed techniques rely on thresholding approaches. Several proposed techniques apply a non linear color transformation on image color space in order to separate specularities and restore colors in bright segmented zones [21, 25]. The main common idea on which based almost specular reflections elimination algorithms consists in segmenting the central reflections part in a first place using thresholding and then segment the surrounding bright region, named also *specular lobe*. The latter is commonly segmented by applying region growing algorithms [26] or morphological operations on the thresholded image.

Based on the assumption that tissues bright parts commonly intersect in color space with weak specular reflections, *Oh et al.* [27] differentiate between strong and weak reflections using multiple thresholds. Similarly, *Jan et al.* [28] propose an hybrid method combining closed contours with thresholding and prove the limited accuracy that can be obtained with thresholding techniques. Other studies mentioned that single threshold techniques include a limited accuracy [29, 27].

A promising idea to explore in this PhD consists in modeling mathematically the optical specular reflections phenomena with respect to the reflectance characteristics of the endo-human tissues so that it will be easier to resolve this problem. Another idea to study consists in using *Inpainting* techniques [30] to fill in specular reflections region with a high quality copy of the same region from a different time frame of the same surgical video scene. The results of both studies are expected to be published in different image processing or medical conferences.

Camera shifting Some of the conventional proposed approaches for video enhancement assume that the camera is fixed which means that the scene is supposed to be exactly the same. However, this is not necessarily the case for laparoscopic videos since the camera might shift even if its hold by a robot such as for the *Da Vinci* Surgical System [2]. In fact, the surgeon needs frequently to zoom in/out or change the perspective in order to switch to a specific part of the surgical scene or capture a new one. In order to solve this problem, a promising idea to test in our research consists in compensating the lost data by embedding complementary redundant information (motion vector for instance) from other temporal images (or spatial view if we are dealing with stereoscopic videos) to create a composite frame including a better description of the scene and more suitable for visual perception.

Surgical smoke, lens fogging and blood pools Surgical smoke and lens fogging are considered as major barriers for surgeons to operate efficiently without threatening the patient safety. In fact, their work is frequently interrupted in order to clean lens fog or evacuate smoke/gas that parasitize their field view. To the best of our knowledge, the literature is poor of solutions addressing this problem. Another useful enhancement feature, that can be explored in this PhD, consists in adapting the contrast to magnify subtle textural variations and thus exhibit the difference between blood vessels and the surrounding tissue, or healthy and diseased tissues such as tumors, which can help the surgeons to achieve fast and safely their surgical tasks.

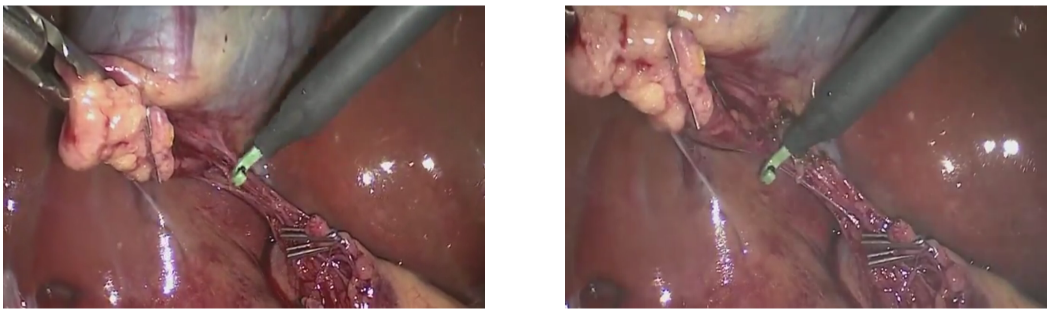

Figure 2: Surgical smoke: the left image represents a surgical view without smoke while the right one shows surgical smoke

Occlusions due to the surgical instruments This problem occurs when a surgical instrument hides another or occludes a surgical organ target, which can affect the surgeon's work efficiency and the safety of the patient.

2.2 Features extraction for 3D surface reconstruction

One of the main challenges for MIS is to determine the intra-operative morphology of the surgical field. As a matter of fact, such information is prerequisite to the registration of the patient-specific data and to the surgeon's navigation capacity by exposing the beyond visible tissues surfaces and providing an efficient control of robotic-assisted surgical systems.

Therefore, nowadays such systems rely on 3D patient-specific models generated from either tomographic modalities like computed tomography (CT) and magnetic resonance imaging (MRI) or other data sources depending on the surgical procedure stage (pre-operative[2] or inta-operative[3]).

The scientific literature is rich of approaches studying the 3D organe reconstruction problem depending on the specifications of the target surgical field and the involved theoretical and implementation techniques. A recent increasingly successful approach relies on the endoscope itself and consists in interpreting the geometry properties of light reflected off the different surfaces representing the surgical site. In [31], the authors classify 3D surface reconstruction techniques into two categories: (*i*) Passive methods requiring only images: stereoscopy, Deformable Shape-from-Motion (DSfM), Shape-from-Shading (SfS) and Simultaneous Localization and Mapping (SLAM) (*ii*) Active methods based on controlled projected light into the target surgical site: Structured Light (SL) and Time-of-Flight (ToF). Table 1 summarizes and compares the most well-known 3D surface reconstruction techniques in MIS.

Table 1: Overview of most well-known 3D surface reconstruction techniques in MIS

Method	Active/ Passive	Additional hardware	Depth range	Lateral resolution	Frame rate
SL	A	Y	Depends on ligh power and sensitivity	Depends on complexity of patterning scheme*	RT
ToF	A	Y	Depends on modulation frequency and light power	Up to 360×240	RT
Stereo	P	N[1]	Depends on baseline	≈Image resolution	RT on GPU
DSfM	P	N	Close range	Up to image resolution	Not yet RT
SfS	P	N	Depends on ligh power and camera sensitivity	Same as image resolution	RT on GPU
SLAM	P	N	Depends on baseline	≈Image resolution	RT

Yes: Y; No: N; Active: A; Passive: P; Real-time: RL;* (typically 0.1-% of image resolution);
[1]requires only a stereo laparoscope

[2]A period before the operation
[3]During the operation

Inspite of the great progress achieved to construct 3D patient-specific anatomy models for MIS, several challenges have not been solved yet and can be summarized in the four following points:

- While many 3D reconstruction approaches ~~assume dealing~~ with a static scene, methods proposed for MIS should take into account the case of a dynamic and deformable ~~environment~~
- Difficulty in detecting and matching automatically salient features for tissues having homogenous texture.
- High accuracy and robustness required to ensure patient safety.
- Complex reflectance properties, non-rigid motions and lack of surface features.

Many approaches have been proposed to extract features from two dimensional images for surface reconstruction. In [32, 33, 34, 35]the authors present different techniques for point and line based graphics. In [36], *Cartmull and Clark* perform rendering by subdividing the surfaces to sub-pixel points using a subdivision scheme for B-spline patches. The same concept was implemented later by *Cook et al.* [37] in the form of “micropolygons” within the Reyes architecture. In [38], the authors introduced the first in-depth discussion of points as graphics primitive. Surface interpolation by a pyramid algorithm was suggested by *Burt* [39] and used in an algorithm by *Gortler et al.* [40]. In spite of the great advances on features extraction techniques from 2D images, only few approaches have been proposed to reconstruct surfaces from stereoscopic images [41, 42, 43]. This is due to 3D images specifications and the related challenges for features extraction, which can be summarized as follows:

- Inter-view differences are difficult to handle specially with occlusions.
- View dependent effects such as specular highlights or reflections lead to correspondence mismatch.
- Difficulty to compute accurate point correspondences in regions with homogeneous color, texture and intensity.

3 Research plan and details

3.1 Research plan

The planning can be organised in three main parts. The first one is related to the PhD and the rest deals with the different research tasks. Following are the stages of the work plan organised in *Work-Package*s (WP) which consists of different *tasks* (T). A gantt chart of the work distribution is presented in Figure 3

WP 1: PhD Management

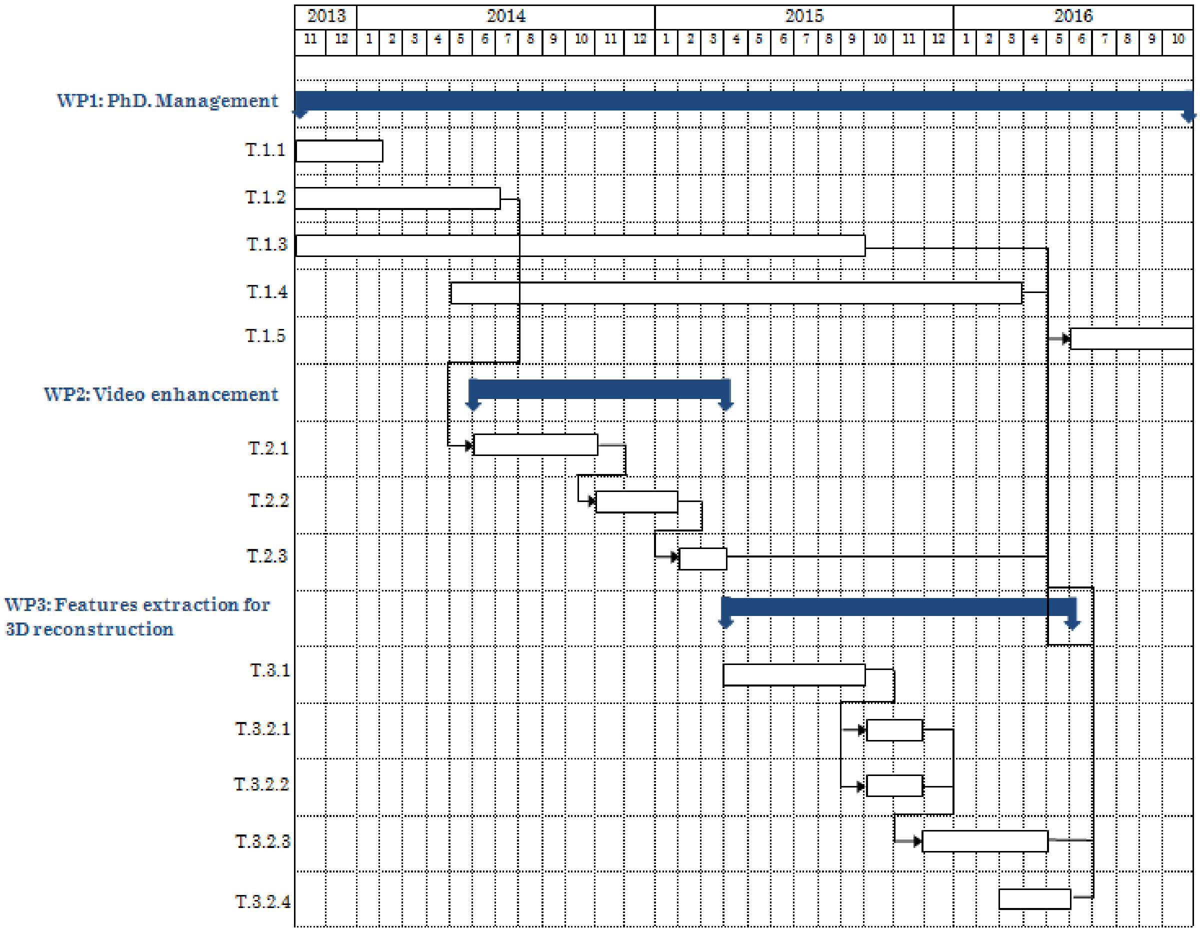

Figure 3: Gantt diagram for the research project

The goal of this part is to set up the main requirements and basis for the research program and the preparation of the scientific outcome for the PhD dissertation.

• **T 1.1 - Research Plan**: This will be prepared and delivered to the admission board at Gjøvik University College for its approval during the first three months of the research

• **T 1.2 - Literature review**: The literature review is extremely important in order to establish the basis and the required background knowledge to support the research process. Another goal of this part is to test the state of the art algorithms based on example videos taken from the *Intervention Center* of *Oslo University Hospital*. The topics that will be reviewed are:

- ❒ 3D laparoscopic video enhancement
- ❒ Features extraction for 3D organ reconstruction and registration
- ❒ 3D organ reconstruction methods from stereo laparoscopic videos

• **T 1.3 - Courses**: As a part of the Phd program several courses will be attended in Paris and in Gjøvik University *College*. Table 2 present the courses that will be attented.

Table 2: List of courses

Course	Institution	Period
Medical Imaging Summer School : Medical Imaging meets Computer Vision	Favignana, Sicily, Italy	July 28 - August 1, 2014 [a]
Statistical methods	Université Paris 13	May 2014
TOEIC preparation and english skills improvement	Université Paris 13	November 2013- June 2014 [b]
Scientific writing and presentation	Université Paris 13	February 2014
Team work and project management	Université Paris 13	not fixed yet (under preparation)

[a]: upon agreement ; [b]: current *TOEIC* score is 790

• **T 1.4 - Publications**: The achievement of the research tasks will produce significant results that can be published in different international conferences and journals. Table 3 show a list of candidate conferences and journals.

• **T 1.5 - Prepare dissertation**

WP 2: Video enhancement

This work package will focus on one of the main research topics of this PhD program, namely laparoscopic 3D video enhancement. The aim is to improve the visual video appearance and provide a better image transform representation for the future processing tasks which include features extraction (T 3.1), 3D surface reconstruction (T 3.2) and registration. In laparoscopic surgery, each of the surgical procedure stages includes different artifact types. Therefore, we split up this work package into the three following tasks:

Journals
Medical Image Analysis
IEEE Transactions on Medical Imaging
IEEE Transactions on Image Processing
Computerized Medical Imaging and Graphics

Conferences
SPIE Medical Imaging
Computer Assisted Radiology and Surgery
International Conference on Computer Vision
IEEE Engeneering in Medecine and Biology Society
IEEE International Conference on Image Processing
Information Processing in Computer-Assisted Interventions

Table 3: Candidate conferences and journals

- **T 2.1 - Remove capture artefacts**: this task will study and develop methods to detect and remove the different capture procedure artifacts such as specular reflections , luminance variation, color mismatch, contrast adjustment, etc. The conventional proposed algorithms addressing such artefacts for 2D videos might be considered and adapted to the stereoscopic video case.
- **T 2.2 - Surgical tasks artifacts**: the aim is to explore and develop methods to address the surgical smoke and lens fogging problem beside compensating the temporarily occluded instruments during the surgery.
- **T 2.3 - Mitigate visual fatigue and discomfort for surgeons**: this task will focus on the visual fatigue problem associated mainly with extended exposure to stereoscopic images/videos. However, the following sub-tasks can also be considered to address the overall visual discomfort problem taking into account the entire visual surgical system:

  ❒ T 2.3.1 : Analyse and identify visual fatigue and discomfort causes related to 3D laparoscopic videos starting form the capture to the visualization stage in the surgical system.

  ❒ T 2.3.2 : Explore methods to reduce the investigated visual fatigue causes. These methods can include video/image processing algorithms or configuration of the surgical video system (camera and display calibration, coding, etc.)

WP 3: Features extraction for organ reconstuction and registration

As mentioned in 2.2, one of the main problems for 3D-patient-specific model reconstruction is the luck of surface features. Moreover, to the best of our knowledge, no work has been proposed to relate 3D organ reconstruction algorithms and its properties with the registration process. The present work-package aims to address this problematic by proposing features extraction algorithms with suitable properties for both 3D surface reconstruction and registration. Since the organ reconstruction study is a part of collaboration with *Gjøvik University College* which addresses the liver resection problem, the following tasks of this work-package will be applied on the liver.

• **T 3.1 - Features extraction**: This task will explore and test features extraction methods for 3D reconstruction and study those which have not been applied before for organ modeling. Based on this study, we will develop a robust features extraction algorithm for natural landmarks-based organ surface reconstruction and registration.

• **T 3.2 - Organ reconstruction form inta-operative stereoscopic video**: This task will be carried out as a part of collaboration with *Gjøvik University College* and consists of four sub-tasks:

- ❒ T 3.2.1 - Study the different conventional methods for 3D organ reconstruction.
- ❒ T 3.2.2 - Use the extracted features (T 3.1) as an input to the investigated 3D modeling algorithms in order to test its performance when applied to a 3D liver reconstruction and registration.
- ❒ T 3.2.3 - In the light of the test results, develop a novel algorithm for 3D liver reconstruction and test its performance.
- ❒ T 3.2.4 - Adjust the features extraction process properties to get a better 3D liver reconstruction and registration performance until optmizing the system.

3.2 Statement of required infrastructure

As a cotutelle PhD student, the required equipment to achieve the research goals will be financed upon agreement by either, *Gjøvik University College*, *Université Paris 13* and *The Intervention Centre* in Oslo. The latter will provide the medical equipment and the clinical environment to integrate and test the developed solutions.

3.3 Statement of Supervision

This research program will be supervised by:

- ❒ Prof. Faouzi Alaya Cheikh, PhD. Gjøvik University College.
- ❒ Prof. Azeddine Beghdadi, PhD. Université Paris 13.
- ❒ Prof. Ole Jakob Elle, PhD. The Intervention Centre, Oslo University Hospital.

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