CHAPTER 2
MATERIALS AND METHODS

The first section of this chapter reviews the current practice in corrective jaw surgery, detailing the conventional method for preparing a surgical plan, as well as the surgical technique used to carry out single jaw surgery with maxillary repositioning. A short orientation on surgical planning transfer methods is described, as well as different technical approaches to the problem in question, particularly Robot Assisted Surgery. An outline of the existing solutions on medical robot coupling is then presented.

Section 2.4 contains a detailed presentation of the mechanical aspect of the developed prototype that answers the raised issues. It explains the novel approach to the proposed problem, with technical drawings, photos of the prototype and explanations of the hardware connections. The prototype was designed with the help of the CAD program, Inventor professional 11 (Autodesk, San Rafael, USA). The manufacturing of the pieces was carried out at the mechanical workshop of the Medical University of Heidelberg.

The next section, 2.5, is a thorough explanation of the image processing and interpretation necessary for the development of the presented prototype. It explains the methods employed to track the 2D markers and perform the position and orientation calculations, as well as camera calibration issues, matching of coordinate systems, FTS interpretation and graphics user interface. The system was implemented under Linux Ubuntu 8.04, employing the open source-image processing libraries OpenCV supported by Willow Garage (Menlo Park, USA).

The final section of this chapter illustrates how the experimental setup was designed to determine the coupling efficiency, forces applied to the patient, stability of the robot arm position during drilling, and screw fixation on a phantom patient as well as on a swine skull.

2.1 SINGLE JAW SURGERY WITH MAXILLARY REPOSITIONING

Before any prospective orthognathic surgery, a systematic examination is necessary to adequately evaluate and plan a treatment for patients with dentofacial deformities. The surgical case this thesis considers is the single jaw surgery with maxillary repositioning; therefore this scenario is given particular emphasis.

2.1.1 HISTORICAL INTRODUCTION

According to the medical dictionary, dysgnathia is an abnormality of the mouth that extends beyond the teeth and includes the maxilla, mandible, or both (89).

Nowadays people usually recognize irregular teeth or obvious jaw deformities and seek treatment from an orthodontist, who can improve tooth alignment, function, and facial
aesthetics. More severe dentofacial deformities require the combination of surgery and orthodontic treatment. This combination makes it now possible to treat dentofacial deformities which could not have been previously corrected by orthodontics alone (142).

Mobilization of the maxilla was first described in the European literature in 1859 (140) by von Langenbeck, who made a horizontal cut, known as an osteotomy. He partially cut through the maxillary bone above the apices of the maxillary teeth and named this procedure osteoplastic resection of the maxilla. Two years later he established the concept of temporary mobilization and inferior displacement of the maxilla by severing a majority of the maxilla from the cranium in the horizontal plane at the level of the pterygopalatine fissure.

In 1901, Rene Le Fort (157) described the classic patterns of fracture. Le Fort's experiments consisted of dropping cadaver skulls from several stories or striking them with a wooden club. He found 3 distinct fracture patterns, which he termed the *linea minoris resistentiae*. Simply stated, the Le Fort I fracture separates the palate from the maxilla, the Le Fort II separates the maxilla from the face, and the Le Fort III results in craniofacial dysjunction.

However, the modern Le Fort I osteotomy downfracture techniques (Figure 1) were not possible until Bell and his co-worker’s research in the mid-1970s’ was conducted. It was with this study on the biologic basis of hemodynamics and vascular supply during and after maxillary down-fracture surgery that the Le Fort I maxillary osteotomy became a reality (142).

![Figure 1 - Various types of Le Fort I osteotomies, ranging from the standard (nonstepped), to the stepped and stepped high Le Fort I. Source: (74)](image)

**2.1.2 CURRENT STANDARD PROCEDURE**

**2.1.2.1 DIAGNOSIS**

The aesthetic equilibrium is studied in several planes, the coronal and lateral examinations being the most important. Symmetry can be evaluated in the coronal plane by comparing facial features on both sides of the facial middle line (mid sagittal line); the lateral plane...
allows profile curvature angles to be measured from a sagittal perspective (Figure 2). Most morphological and aesthetic analyses generally distinguish three levels in the face: the upper third from the hairline (trichion) to the glabella, the middle third from the glabella to the subnasale, and the lower third from the subnasale to the soft tissue menton. This lower third is also divided into three sub-levels. In a well-proportioned face, all these levels are of equal size and parallel to the horizontal plane. Facial width should be at its maximum between the two zygomatic arches and mandibular angles. Natural exposure of superior incisors with lips at rest should be from 1 to 5mm, and around 8mm while smiling. However, facial proportions are only idealized concepts and change over time. They merely provide a guideline that is not true for every patient (130). Conventional means to measure the degree of dentofacial deformity range from photographic documentation and detailed analysis of radiographs (referred to as the cephalometric study), to dental cast models.

![Figure 2 - Coronal and lateral evaluation. Source: (87)](image)

The correct dental occlusion plays an essential role in masticatory function as well as in facial aesthetics; therefore this problem is firstly evaluated by oral examination. According to Angle (20), relative position of dental arches in the horizontal plane define the occlusion class (Figure 3):

- **class I**: normal occlusion - the upper dental arch is slightly anterior to the lower arch, from half a cusp.
- **class II**: the upper dental arch is anterior to the lower arch.
- **class III**: the upper dental arch is posterior to the lower arch.

![Figure 3 - Occlusion classes according to Angle’s classification. From left to right, class I (normal), class II and III. Source: (76).](image)
Also employed throughout this thesis are the accepted terms in dentistry used to describe the relationship between the dentition of the upper and lower jaw (20):

- **overjet**: horizontal gap between the incisal edges of the maxillary incisor and the mandibular incisor.
- **cross-bite**: lingual-buccal inversion of the normal relation between upper and lower dentition (negative overjet).
- **overbite**: an extension of the upper teeth on the lower teeth in the vertical plane.
- **deep bite**: condition of extreme overbite, where the lower teeth may be hidden behind the upper teeth.
- **open bite**: condition of negative overbite (teeth do not meet).

**Cephalometric evaluation**

Routine radiographic evaluations typically include orthopanorex, frontal and lateral radiographs. Orthopanorex X-rays (Figure 5) provide an overview of the stage of dental development, the mandibular anatomy, and gross pathology. Cephalometric x-rays (Figure 6) provide standardized skull and/or facial views that allow comparison over time to assess dentofacial architecture and growth in an individual, as well as comparison of that individual against standardized population norms. Frontal cephalometric x-rays allow assessment of the degree of facial asymmetry. Lateral cephalometric x-rays allow assessment of elements of the dentofacial skeleton from the sagittal plane. Objective and quantitative evaluation is possible by measuring angles and distances between the different structures of the facial skeleton and adjacent soft tissues, on which a treatment plan can be based (155) (125). For the surgeon, this analysis must be clinically workable, simple to use, and directly applicable in surgery. The amount of bone movement and directions acquired at this stage are fundamental for later use.

Available nowadays are many software tools that perform numerous standard cephalometric analyses based on digital scans of the cephalometric x-rays. These software applications provide a partial answer to the limits in precision of conventional (pen and paper) cephalometric techniques. Some of these tools are further described in section 2.2.1 - Surgical planning software.
Dental cast models

Impressions of the teeth are taken with a solidifying gel and allow the fabrication of dental cast models (Figure 7). Careful analysis of the models by both surgeon and orthodontist is essential to conduct a suitable pre-surgical orthodontic treatment. The maxillary and mandibular dental casts can be studied individually and manipulated with one another to assess how arches coordinate. This evaluation includes space analysis and arch length, transverse width discrepancies, position of individual teeth within the arch, and maxillo-mandibular relationship.

Registration is required to allow cast models to be placed correctly in relationship to the temporo-mandibular joint, for which a facebow is used (Figure 10).
2.1.2.2 SURGICAL PLANNING

After the initial diagnosis, a pre-surgical orthodontic treatment is frequently undertaken. During this phase the dentition is orthodontically aligned within the dental arch without any attempt to correct the occlusion. Frequently this temporarily worsens the malocclusion, but it shapes the dentition to a correct position with regards to the expected result of the surgery. This pre-surgical phase varies from 6 to 18 months depending on the patient’s needs.

Planning is realised with X-ray and dental cast models, shortly before the surgery is performed. Movements of the skeletal units are calculated on the cephalometric study, while relative positions of the jaws are reproduced on the dental cast models.

Cephalometric analysis

Cephalometric analysis depends on radiographs to study the relationships between bone and soft tissue landmarks, and is used to calculate the discrepancies between the several different landmarks. Three of the most popular methods of analysis used in orthodontology are the Steiner analysis (168), the Ricketts analysis (143) and the McNamara analysis (121) (Figure 8).

Skeletal movement simulation is realised on a tracing of the cephalometric analysis, against which contours of upper and lower jaw are drawn and cut.

Every analysis method has its characteristics and provides more or less quantitative information. The calculation method used is highly dependent on the orthodontist’s preferences; however, in the end the important and relevant information is must be extracted and clinically workable. This information will determine the appropriate treatment plan; the required surgical intervention, displacement, directions and which jaws require repositioning.

The combined maxillary and mandibular movements are referred to as bi-maxillary osteotomy, as opposed to mono-maxillary osteotomy. If necessary the position of the menton is evaluated, and genioplasty indications are given by aesthetical criteria (rather than cephalometric) (181).
**Figure 8 - Three possible cephalometric analyses, (a) Steiner, (b) Ricketts and (c) McNamara.**
Sources: (168), (143) and (181).

**Dental cast model simulation**

The bulk of the calculations required to correct the dentofacial deformity are performed during the cephalometric simulation. The dental cast simulation is then carried out to reflect the corrections in occlusion introduced by the planned bone movements. In order to do so, the cast models of the patient’s teeth are placed on a mechanical apparatus called an articulator (Figure 9). Registration between the cast models and the patient is performed with a facebow (Figure 10) which allows the correct positioning of the cast models in pre-operative occlusion and an exact reproduction of the temporomandibular joint on the articulator.

Markings are made on the bases of the plaster casts to measure the movements which will be realised on the articulator. The casts are then cut and moved according to the cephalometric calculations (Figure 11).

**Figure 9 - Articulator.**
The mandible, especially the mandibular incisors, determines the new anteroposterior position of the maxilla. However, the surgeon may alter the vertical height with superior or inferior repositioning of the maxilla. When the maxilla is superiorly repositioned (vertical maxillary excess) or downgrafted (vertical maxillary deficiency), the mandible will autorotate around the condyle. The target position of the maxillary incisors is determined by the anteroposterior position of the mandibular incisors after this autorotation. If necessary the orthodontist should compensate the incisors for this “added” advancement of the maxilla. This may require retracting the mandibular incisors slightly or may necessitate two-jaw surgery if the anteroposterior discrepancy becomes too large to be treated by a single-jaw surgery.

Transverse discrepancies (narrowing or widening), vertical occlusal plane discrepancies (open bites), and interdental spaces in the maxillary arch may be corrected by segmental surgery.
When deciding on the final position of the bone segments, it is verified that the dental occlusion is correct and confirms the previous calculations. Special attention is also given to soft tissue tolerances and limitations for later internal fixation.

The simulation of these movements on dental cast models allows the fabrication of dental splints, which are made of an acrylic resin that moulds to the dental impressions of both upper and lower jaw. This splint allows the correct placement of the maxilla in relationship to the mandible and is the central piece in transferring the preoperative surgical plan to the operation room.

### 2.1.2.3 SURGICAL PROCEDURE

Orthognathic surgery is a meticulous and lengthy procedure (1h30-2h30 for monomaxillary osteotomy, 3h30-4h for bi-maxillary osteotomy, 4h-5h for bi-maxillary osteotomy with subsequent genioplasty). Since the approach is endobuccal, intraoperative ventilation is achieved by nasotrachea intubation (Figure 12). Heamorrhage is an important issue, especially during maxillary osteotomy. The surgery is performed under general anaesthesia resorting to the use of hypotensive anaesthesia in order to reduce blood loss, the need for blood transfusions and special instrument sets (12).

![Figure 12 - Intraoperative nasotrachea intubation.](image)

**Maxillary osteotomy (Le Fort I)**

The horizontal osteotomy cut, known as Le Fort I, allows complete mobilization of the maxillary segment. It can be associated with a mid-sagittal osteotomy of the maxilla in order to modify the palate width. In bi-maxillary osteotomy, the maxillary osteotomy is typically performed first, the mandibular segment being repositioned in a second step on the now-corrected maxillary segment.

The initial approach is to expose the midfacial skeleton via an intraoral labiobuccal incision 2mm above the attached gingiva, from one first molar to the first molar on the opposite side, up to the inferior orbital foramen (Figure 13).
Prior to the osteotomy, a pre-planned osteotomy line can be traced using a ballpoint drill on the anterior maxillary wall. The cut itself is performed using a reciprocating saw or long drill. Once the osteotomy is completed, separation of the maxilla from the cranial base is finalised by detaching the maxilla from the pterygoid plates (posterior to the maxilla) and downfracture of the segment (Figure 13).

When down-fracturing the maxilla by pushing it downward, excessive force should be avoided because:

- It may mobilise the maxillary teeth. The teeth may be slightly mobile due to the pre-surgical orthodontic treatment.
- Prolonged and excessive pressure on the maxillary gingiva may compromise the blood supply.
- It may loosen the orthodontic brackets on the anterior teeth.
- It may cause the maxilla to fracture unfavourably (eg, fracture through the palatine bone or the pterygoid plates, resulting in excessive haemorrhage and / or difficult repositioning of the maxilla).

Maxilla repositioning

Once the maxillary fragment is mobile, upper and lower jaw are brought together on the dental splint fabricated during the pre-operative planning. The dental arches are bound together by wiring the upper and lower brackets together, forming a maxillomandibular complex, which is free to rotate within the temporo-mandibular joint (Figure 14).
The splint defines the occlusal situation and allows the maxilla to be placed in the desired final position relative to the untouched mandible, though only in the horizontal plane. Repositioning of the maxilla in the vertical plane remains a challenging task, carried out by holding the mandible in a stable position approximating as much as possible to a normal situation. This normal position is defined as the location where the mandible is correctly placed in the articulation, and not relaxed under anaesthetics. At this point height measurements are taken with a compass or ruler and compared to measurements taken with the cephalometric calculation (27) (Figure 15).

For vertical maxillary excess (upward movement), bone at the contact points must be selectively removed; likewise, in cases of significant inferior repositioning (5mm or more of vertical maxillary deficiency), interpositional bone grafts are inserted to fill the gaps. When the maxilla is thought to be in the desired position, it can be stabilized with plates and screws.

During this period the maxillomandibular complex is again held manually by the assistant surgeon in the desired target position.

The maxillary-mandibular fixation can then be released to verify that the mandible passively closes directly into the splint. Slight adjustments can be made to the position thanks to the slight degree of flexibility of the plates. If it is suspected that the mandibular condyles were not seated properly at the time of fixation the repositioning procedure must be repeated.
Final rigid fixation is achieved with four miniplates, each located on the anterior maxillary wall with miniscrews (Figure 16).

![Figure 16 - Left: Model showing 1.5-mm plates attached across a Le Fort I level Osteotomy. Right: Model demonstrating proper placement of plate and screw fixation. Source: (75).](image)

**Postoperative follow-up**

Hospitalization lasts about five days for maxillary or bi-maxillary osteotomy. Depending on the perceived level of stability, maxillary-mandibular fixation is maintained with wire or dental elastics for a period of two to eight weeks. If the occlusion changes, elastics can be applied with an appropriate vector to guide the occlusion until bone healing is completed. This phase typically lasts between four to six months and ends with the removal of the orthodontic brackets. The internal osteosynthesis material can be later removed in a second surgical procedure.

**2.1.3 FUTURE PERSPECTIVES FOR DYSGNATHIA SURGERY**

While the last 150 years were distinguished by the creation and standardization of surgical methods (Figure 17), in present days the focus lies on precise treatment planning and considerations of functional aspects of the whole stomatognathic system (140). Research has provided tools that allow the execution of surgeries of complex cases with accurate predictions of surgery outcome and of soft tissue changes, such as enhancement of visualization with 3D patient views acquired with CT and MRI scans (122), analysis and diagnostic tools (192), interactive repositioning of bone fracture segments (153) (72), automatic reconstruction of missing or malformed bone structures (194) and finally computer-aided treatment planning and simulation tools (132) (148) (124) (10).

In addition to these examples, other research efforts have developed a variety of advanced techniques to help reposition maxilla and mandible, going beyond simple dataset viewers used for diagnostics or planning. With the intention of increasing the accuracy achieved with the present methods Chapuis in 2005 (29) introduced a navigated approach to maxilla repositioning. In addition, a navigation system for repositioning of CMF bones was presented by Marmulla (117). An active surgical robot system (OTTO) in the same clinical
environment was first presented in 1998 (110). OTTO was used for inserting nonflexible catheters and implanting bone fixtures in the skull. More recently and specifically for orthognathic surgery, a technical solution using a robot has been presented by Burger (22). Although not tested yet on actual patients, the system intends to accurately point the target position for the single jaw surgery with maxillary repositioning.

![Figure 17 - Bi-maxillary treatment evolution, from the left: Three years before surgery; One year before surgery with orthodontic treatment; Pre-surgical image acquisition; Two days after surgery.](image)

### 2.2 COMPUTER AIDED SOLUTIONS FOR CRANIO-MAXILLOFACIAL SURGERY

For many centuries medical doctors and scientists actively studied the form of the human skull and its possible congenital deformations. Corrective surgeries in the CMF area have since then developed unique characteristics and requirements, one of them being the necessity of even greater accuracy in execution. Such requirements for higher accuracy have lead to the development of technically challenging solutions (146). They are intended in particular to improve the planning transfer to the OR (131). For this reason, many research efforts have developed increasingly sophisticated tools to help surgeons plan and execute their interventions. Understanding the limitations of the existing technologies will help to determine their usage (140), specifically for the presented surgical case.

#### 2.2.1 SURGICAL PLANNING SOFTWARE

Many manufacturers of medical solutions market their surgical planning software together with the transfer equipment for a seamless integrated solution. There are however still many research topics and companies investing in the development of standalone planning software tools. They generally aim at specific issues or known problems such as soft tissue prediction, enhancement of visualization / analysis and diagnostic tools.

Orthognathic surgery or bone repositioning surgery in the CMF area imposes certain requirements with which software tools must comply. A minimum requirement for such a
software tool is the ability to transfer the relevant data to an intraoperative situation by any
technological means. Additional requirements would include user-friendliness, diagnostic
assistance, anatomical atlas reference, etc, depending on the medical application and
necessity.

At the point where the surgeon prepares a diagnostic and subsequent surgical plan, CT
image data, MRI or X-Rays are already digitally available. To some extent it is also
possible to correlate cast models with a software tool, as demonstrated by Chapuis in 2006
(27) (28). Using the available data the surgeon is able to prepare the intervention and
intraoperatively is expected to use that additional information and plan. In this section
these requirements and how they are implemented are analyzed.

In 1993, Altobelli (5) researched planning software for craniofacial surgery which resulted
in the integration of cephalometric and anthropometric databases with three-dimensional
CT reconstructions to assess the facial deformity and to assist in the planning of the
surgical procedure. The software allowed interactive techniques to simulate osteotomies
and skeletal movements in three dimensions on the computer-generated patient model to be
employed. The osteotomized ocular segments were transposed into normal anatomic
relationship using a mirroring technique, expressive of facial harmony (100). The
measurements given by the surgical planning tool were then transcribed by hand and used
intraoperatively to establish the target position of the bone segments. Although an
interesting planning tool, the ability to transfer the surgical plan was left to manual
translations based on the measurements acquired by the planning tool. This problem is
found in most planning software tools but it helps the surgeon to overcome the
computational load involving bone repositioning surgeries.

A recent development for computer-aided orthognathic surgery was presented by Chapuis
in 2006 (27) (28). It combines 3D surgical planning with conventional dental splints. In a
simulation environment the surgeon is able to observe the 3D virtual model of the patient’s
facial skeleton, generated from CT scans. The surgical planning simulation includes
dynamic cephalometry, semi-automatic mirroring and interactive cutting of the bone with
subsequent repositioning.

In order to create the dental splints, the planning software correlates the virtual jaw model
with the pre-acquired dental cast models. A pre-fabricated registration splint is tracked in
an articulator with dynamic reference frames specially designed for this purpose. The
required splints are then obtained by mimicking the desired bite on the articulator,
followed by the production of intermediary and final splints.

By placing landmarks at the base of the osteotomized jaw, the software additionally
estimates the amount of bone to be removed for upwards displacement.

Intraoperatively the surgeon is assisted with a navigation system. The patient is firstly
placed in a Mayfield clamp, or tracked with a specific cranial tripod, necessary for
registration. The registration splint will then be used to correlate the computer model with
the patient in surgery. The surgical procedure follows the conventional workflow
employing the fabricated splints. The surgeon has then the aid of the navigation tool which
shows if the occlusion and repositioning is being performed in accordance with the
preoperative plan. The system has been applied to one patient at the time of writing, with
the conclusion that the assessment of the pathology was improved and the surgical procedure control was enhanced.

2.2.2 PLASTIC TEMPLATES AS SURGICAL PLAN TRANSFER TOOL

In single jaw surgery with maxillary repositioning the current method of surgical plan transfer is the use of a plastic splint with the dental impressions of both upper and lower jaw (Figure 14) (142), as well as compass measurements of the bone segment displacement (Figure 15).

For more complex craniofacial reconstructions stereotactic devices have been used since 1992. For example, a head frame applied to the patient’s head without any direct bony fixations, using the external auditory meati (EAM) bilaterally and a custom-made rigid dental splint (60) (38). Fixation at the EAM provided the required stability to the head frame.

In orthognathic surgery, the conventional approach requires no computational methods; therefore, the dental splint and visual confirmation of displacement measurements are the main sources of accuracy error. Targeting for repositioning in this procedure is traditionally carried out in a non-interactive fashion, without real-time position feedback.

Comparing stereotactic solutions in terms of accuracy with other computer assisted solutions, recent reports on robotic systems outperform both frame-based and navigated systems, where the robot is able to achieve accuracies of 0.5mm whereas stereotactic frames have 0.98mm and frameless systems 1.96mm (51). There are currently no assessment studies on accuracy achieved in orthognathic surgery using plastic splints.

In the field of CMF, and referring to plastic bone templates, Mimics (Materialise2, Leuven, Belgium) is a 3D image processing program that translates scanner data in to 3D models, finite element meshes and rapid prototyping. The program allows the simulation of surgical procedures, creation of movies and reports, cephalometric evaluations and recreation of missing bone fragments. In the simulation module a variety of osteotomies and distraction surgeries can be simulated and perform detailed analysis. With this program the surgeon can virtually recreate missing bone fragments easily and evaluate symmetry. For transferring this information to the OR the software can be connected to a rapid prototyping machine. Missing bone segments are then created and can be used in surgery for various situations (Figure 18).

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2 www.materialise.com
2.2.3 SUPPORTING TECHNOLOGIES FOR PREOPERATIVE PLAN TRANSFER

Several issues are pertinent when transferring computer surgical plans to the OR. Here it is necessary to understand what influences the outcome of a surgery in terms of accuracy, safety, usability and comfort for both patients and surgical staff.

Registration correlates the unknown spatial relationship between the preoperative data (CT, MRI, X-Rays, and surgical plan) with the in-situ physical patient on the operating table. A correct registration is fundamental for achieving an accurate planning transfer, and a short analysis is conducted here.

Tracking is another pertinent issue since it maintains the relationship between the registered data and the patient throughout the surgery. Different technologies are available to solve this problem, each with different characteristics and accuracies, which should be discussed individually.

Intraoperative image acquisition and update supports image guided surgery technologies and enables accurate and viable intraoperative surgical planning updates.

2.2.3.1 REGISTRATION

Registration is not only fundamental for a successful Computer Assisted Surgery (CAS), but a simple and effective registration step is required for public acceptance of computer and robotic techniques. This step is often time-consuming and incurs the risk of introducing errors or misinterpretations (184). Therefore, new registration methods are the main focus of many research projects’ efforts, attesting that this time-consuming step tends to be minimised in time consumption or altogether eliminated (automatic registration) (48) (138) (104) (115). Understanding the differences between these registration processes and their expected impact will help to determine the better course of action (97) (114).

Fiducial markers
One of the most common registration techniques involves the placement of bone-implanted fiducial markers (normally titanium screws). The screws are attached to the patient’s cranium prior to a pre-operative CT or MRI scan, and can be identified and localized automatically by the computer within the pre-operative images. Intra-operatively, the fiducial markers are physically exposed, and the locations of these markers are measured using an intra-operative sensing device (as described in section 2.2.3.2 -
Tracking). This is currently the gold standard confirmed by several researchers (118) (113) (163) (61) (26).

**Surface matching**

The method consists of correlating image data and patient by means of comparison of several random points (acquired by pointer or laser) with a previously acquired 3D model of the patient. Although this method does not yet yield the same accuracy as the fiducial markers they are regarded as an advance due to the lack of preoperative incisions to insert screws on the bone.

One of the first to test the accuracy this method was Ryan in 1996 (146), by inputting randomly chosen scalp points with a tracked stylus pointer and fitting them to a scalp surface model derived from MRI. This series of navigated surgery experiments found an average and standard deviation between the actual position and the stereotactically predicted location of 4.8±3.5mm. Other researchers in the mean time have increased this accuracy (116).

**Dental splints as registration markers**

A new concept has been tested by some researchers where the fiducial markers are not bone implanted but are instead placed in an external dental splint which is attached pre- and intraoperatively (109) (28).

**Comparison of registration methods**

In 2008 Luebbers (109) tested four different registration methods. A synthetic full size human skull model was registered with its CT dataset using: 1- a dentally mounted occlusal splint; 2- a laser surface scanning; 3- five facial bone implants; 4- a combination of dental splint and two orbital bone implants. The TRE was computed for 170 landmarks spread over the entire skull and an average accuracy of 1mm was found for the periorbital region regardless of the registration method. Considering the simplicity of registration using a dental splint, the interest in this form is naturally high. Consequently, more efforts have been made to improve the poor precision yield from the dental splint for navigation beyond the mid-face, and its accuracy can be increased by combining the splint with two bone implants inserted percutaneously on the lateral orbital rim on either side.

Additional efforts are being spent on device integration to produce easy registration procedures for a variety of surgical applications, with the highest number of devices.
2.2.3.2 TRACKING

Patient tracking is not an addressed issue in this research, but it is paramount for the overall system performance. It maintains the relationship between the registered data and the patient throughout the surgery. To solve this problem there are a number of technologies available, such as:

- **Optical tracking and photogrammetry**

Robot manufacturers have used photogrammetry for several years in order to carry out calibrations and monitoring of factory floors (82). Now other non-technical areas have profited from this technique as well. These systems work by triangulating the position of distinctive visual markers or infra-red (IR) emitters / reflectors. Active IR markers contain infra-red emitting diodes which will be tracked. In the case of passive IR markers there is an infra-red emitter close to the cameras. Visual optical markers with distinctive patterns are also used for tracking. A minimum set of 3 markers is required on each tracking body to accurately determine its position and orientation. A constant line-of-sight to the markers is also required.

- **Mechanical**

This type of tracking refers to the readings of a robot arm position. Each joint contains encoders that tell the robot controller the current position of the robotic arm. It is highly accurate when tracking the tool at the end of the robotic arm, but impossible to track loosely or completely disconnected hand-held tools (159).

- **Electromagnetic tracking**

Electromagnetic tracking devices function by measuring the strength of the magnetic fields generated by three small coils perpendicular to each other. These coils are inserted in the markers and by sequentially activating each of the coils and measuring the resultant magnetic field, it is possible to determine the position and orientation of the marker. This type of tracking is useful that it does not require a line-of-sight to the tracking bodies; however, it suffers significantly from electromagnetic interference. This method is therefore unsuitable for use in areas with large amounts of metal, cabling or electric motors such as drills (182).

- **Ultrasound**

By measuring the distance between a network of piezoelectric transducers and high frequency digital counters, the tracking system can find and triangulate 3D positions from each transducer. The advantages of this system are its simplicity, effectiveness and safety. On the downside though, the system is spatially restricted, sensitive to temperature, and as with optical tracking systems, also requires line of sight (164) (70).

The existing tracking technologies can be summarized in the following table:
Table 4 - Comparison of tracking methods, updated from (162).

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<th>MAGNETIC</th>
<th>ULTRASOUND</th>
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A more advanced application of tracking technology is internal organ motion tracking. For example, Ginhoux (71) published some results attempting to track the beating heart using active optical markers on the heart and fast 500Hz video cameras.

Although many studies indicate the feasibility of these tracking technologies, and their particular usage in specific cases, it is also recognized that the system with the best relation limitations versus highest tracking accuracy is the optical tracking. Highly effective and accurate, this technique for localisation has as biggest disadvantage the requirement for maintenance of ‘line-of-sight’ with the cameras (18) (107) (80).

### 2.2.3.3 INTRAOPERATIVE IMAGE AND PLANNING UPDATE

Regardless of a successful registration of the preoperative images and surgical plan with the patient, another problem tends to occur with image guided surgery where throughout the surgery there is a growing discrepancy between the images acquired preoperatively and the patient himself. For example, a foreign body might dislodge; it might be required to detect additional tumours; or the target area may even not match with the preoperative images. In neurosurgery a typical example of this problem is the brain shift, immediately after craniotomy, and due to tissue manipulation.

In the case study of dysgnathia this problem is non-existent since shortly before surgery new dental impressions are acquired, and the relevant structures do not change significantly until and during surgery. Nevertheless, in the interest of technology coherence a small reference to this issue is due.

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3 www.faro.com  
4 www.brainvoyager.com  
5 www.brainlab.com  
6 www.ndigital.com  
7 www.atracsys.com  
8 www.clarontech.com/  
9 www.polhemus.com  
10 www.ascension-tech.com  
11 www.medtronicnavigation.com  
12 www.inition.co.uk
The current common practice for updating the surgical plan has been to update the
computer generated models with a new image data scan, new registration and possible
adaptation of the preoperative surgical plan (162).

Three technologies are available for this purpose. 3D ultrasound, for example, does not
convey the same amount of detail as the alternatives (102) (35) (147), but has already
reached an acceptable level of tissue detail. It is used mainly to detect liver neoplasms or
similar metastases in other regions of the human body immediately prior to operation (53);
it is only rarely used in CMF surgery and seldom in neurosurgery (108) (30) (77). Intraoperative CT
as a surgical image update technology has the problem of radiation exposure affecting not only the patient but the medical staff as well (25). Currently Intraoperative CT is used in spine surgery (198).

Intraoperative MRI (IMRI) therefore has potential advantages. Used in neurosurgery in
particular, IMRI produces excellent soft tissue contrast, precision, and of course, the ability
to visualize tissue changes such as brain shifts and acute complications within the
anatomical region directly during surgery. Although there are problems regarding this
technology, such as the placement of metal in the proximity of the device, several
commercial devices are available and have proven viable (19) (188) (187) (6).

2.2.4 NAVIGATION SYSTEMS

Ostertag in 1999 (129), considered that there was an unreflected enthusiasm towards high
tech solutions, with little advantages in accuracy and patient outcome (referring to
neurosurgery). However, nowadays one can easily perceive the importance of navigation
systems, and pronounce them as in widespread use (172) (2). Navigation systems show the
surgeon in real-time the location of the hand-held tool with respect to the preoperative CT
or MRI dataset previously acquired. These systems are normally used to trace anatomical
structures, tumours and foreign bodies, but can also be used for bone repositioning. For the
latter purpose, the navigation systems must be able to describe and map the mobile bone
segments in 3D in relationship with the rest of the skull (117) (3).

Cutting’s (39) initial design of a virtual reality approach was later taken further by others
and Marmulla's Surgical Segment Navigator (SSN) (117) was one of the first to
successfully implement the concept. The SSN is based on an infrared positioning tracking
device connected to individual templates which are fixed to the bone segment by
osteosynthesis screws. Intraoperative correlation between surgical planning and the
surgical site is achieved through the use of a surface-pattern of the bone segment which fits
equally well to the laboratory model and the conditions encountered in the patient. The
updated version, the SSN++ already uses a markerless registration procedure (116). The
evaluated precision of the SNN Navigation system claims a discrepancy between the
obtained transformation and their planned targets in the ranges between 0.3 mm and 1.1
mm with a mean error of 0.7 mm, a standard deviation of 0.2 mm and 95% percent of
errors under 1 mm.

Of particular interest for the hypothesis presented in this thesis is the work of Chapuis (27)
(28). In 2006 a new system for Computer-Aided preoperative planning and intraoperative
navigation during corrective jaw surgery was presented. The system combines 3D surgical
planning with conventional dental occlusion planning. It allows simulation of the surgical
correction on virtual 3D models of the patient’s facial skeleton. With the help of a special
registration procedure, this system is able to acquire dental occlusion plans from conventional cast models. From the cast models a special registration splint is constructed. This splint has the dental impressions of the patient and tracking markers.

Intraoperatively the patient is either placed in a Mayfield clamp, or tracked with a specific cranial tripod. The constructed registration splint will then be used to correlate the computer model with the patient in surgery. The surgical procedure follows conventionally using the fabricated splints, with the aid of the navigation tool that shows if the occlusion and repositioning is being performed as expected. The surgeon uses the navigation system to obtain the position information, suitably indicated by two cubes. One fixed, representing the final target position; and the second rotating around the three axes, indicative of the current position of the maxilla. The correct orientation is reached when the two cubes are aligned with one another. The results obtained indicate a precision within 1mm and one degree.

The proposed approach combines the advantages of 3D visualization and tracking technology with cast based techniques for dental occlusion evaluation. The system has been applied on only one patient at the time of writing.

### 2.2.5 AUGMENTED AND VIRTUAL REALITY SYSTEMS

The use of Augmented Reality systems (AR) in surgery aims to enhance the already existing navigation systems. Instead of forcing the surgeon to constantly look away from the patient and at the computer screen, augmented reality systems provide real time feedback directly into the surgeon’s visual field (49) (190) (161).

There are three classifications of AR systems. Optical see-through, Video see-through and projector based. The differences are subtle but relevant; while optical see-through displays allow the surgeon to see the real world, regardless of what calculations and virtual information is super-imposed, video see-through relies on camera feedback and displays in a small monitor the whole combined scene. Consequently, optical see-through is safer in case of failure or mismatch and has no time delay for the real world view, while the only advantage of video see-through is the higher flexibility in scene composition and calibration strategies. Both of them are available in head-mounted displays. In projector-based AR, the system projects over the tracked scene the relevant information (93).

In 1997, Watzinger (183) was one of the first to experiment with AR technology in a surgical concept. The test surgery was a reconstruction of post-traumatic unilateral deformities of the zygomaticomaxillary complex, and five patients where tested. The computer procedure was planned by drawing graphic lines on the CT scan and the desired position of the displaced zygoma was planned by mirroring from the healthy side, using a virtual mid-sagittal plane. These virtual graphics were presented intraoperatively on a computer screen as well as on the surgeon's see-through head-mounted display. Although the obtained results were satisfactory in all studied cases, the claimed advantages where already present in simple navigation systems and no planning transfer accuracy was assessed. Another AR tool named X-Scope® for CMF was also presented in 2006 (123). X-Scope allows visual tracking of real anatomical structures in superposition with volume rendered CT or MRI scans for navigated repositioning of bony segments. The technique was used in orthognathic surgery to control the target position of the maxilla after Le Fort I osteotomy within a bimaxillary procedure. The feasibility study with five patients reported a repositioning accuracy within 1 mm, and it was asserted that a stand-alone application without conventional control does not yet seem reasonable.
In projector-based AR, several projects try to alleviate the bothersome use of head-mounted displays. Projector-based AR systems produce the computer generated models and information directly over the patient in a way that the surgeon is expected to see. They still require the tracking of the surgeon’s field-of-view in order to manipulate the matching of the intraoperative situation with the pre-planned image acquisition and segmentation. It is therefore usual for the surgeon to carry a cap or similar containing a tracking body (170) (90). Accuracies in projector based AR were measured by Krempien (101) with obtained results of 1.4 mm, within the a range of 0.3 to 2.7mm. The studied medical cases were interstitial brachytherapy and implant insertion.

An alternative to the usage of either head-mounted displays or projectors is by augmenting images of already existing surgical tools, for example endoscope (34) or microscope (95). Aschke (7) introduced a 3D overlay of a patient model on the operating field using a standard neurosurgical microscope. Preoperatively acquired data is inserted into the optics of the operating microscope, giving the surgeon the three-dimensional information previously specified. King (95) presented the same concept, except with segmented preoperative radiological images.

![Figure 19 - AR microscope view. Left: Phantom with craniotomy opening. Right: Phantom with over-imposed brain, simulating brain shift. Source (119).](image)

### 2.2.6 ROBOTIC SYSTEMS

Surgical planning software has become more accurate and precise than surgeons are able to execute (38) (99) (42). On the other hand, the usage of robots in surgery often raises issues such as safety, ethics and usability (85) (55) (99). Although the focus of this thesis lies in CMF surgery, and in particular maxillary bone repositioning, it is necessary to discuss the first successes of this area, even when they were first applied in other medical specialties.

For example, the well-known ROBODOC® for hip replacement surgeries from Integrated Surgical Systems, Inc (ISS)\(^\text{13}\) was considered a success for many years and compared with

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\(^{13}\) Since 1997 ISS purchased NeuroMate\(^\text{TM}\), and in September 2007 due to a partnership with Curexco Technology Corporation changed the name to ROBODOC.
manual practices produced radiographically superior implant fittings while eliminating femoral fractures (137) (179). The NeuroMate™ robot, also commercialised by ROBODOC (Sacramento, USA), was the first neuro-robotic device to be approved by the U. S. A. Food and Drug Administration (FDA) in May 1997. The NeuroMate system positions, orients and manipulates the operating tools holding them exactly as previously determined by the surgeon on the image planning workstation. Preoperative imaging helps the surgeon plan the procedure, and a passive robotic arm was able to perform limited tasks in over 1000 procedures (127) (120). However, this technology is prone to errors such as brain shift (175). A clinical study has assessed the accuracy of this system and showed that application accuracy less the 2 mm could be achieved in routine clinical practice (13).

A solution for cranial bone osteotomies was recently tested by Eggers (50). The RobaKa system, developed at both Karlsruhe and Heidelberg Universities, is capable of controlled bone milling for craniotomy on a patient (Figure 20). Preoperatively, a set of complex osteotomies for reshaping the cranial vault are planned using the KasOp software (156). Intraoperatively, a registration procedure recognizes the location of the fiducial markers by dragging the robotic arm in force-control mode, with a registration pointer in its tip. With a fixed robot base, the system calculates the real world to virtual world registration offset. The geometry of the skull is thus known, and where to cut the trajectory is therefore also defined.

Safety is ensured by redundant control architecture: position and orientation of the robotic instrument is monitored via infrared navigation system, which can shut down the operation immediately in case of abnormal behaviour. In addition, the robot remains in operation while two buttons are held pressed, and a metal jacket around the drill limits the maximum intrusion into the skull (98) (55).

Figure 20 - RobaKa system in surgery.

A new concept for RAS was presented by Kane in 2009 (92). Kane proposed the use of a small handheld mobile robot developed for performing craniotomies named Craniostar (Figure 21). The pre-planned craniotomy trajectory is simulated before surgery on the
computer, and the trajectory is precisely transferred to the OR with minimum modifications to the surgery workflow. This mobile surgical robot demonstrated the ability to achieve the same accuracies as current surgical systems, but brings the surgeon's experience and intuition into the play as its own system inputs. The system combines the required craniotomy drill, drill torques and current standard optical tracking system as inputs and guides the hand of the surgeon in the pre-planned path on the patient’s skull. As the surgeon leans the robot forward it intuitively starts performing the trajectory as planned, if leaned backwards it follows the cut path rearwards. This approach is still under development and further testing is required to assert the intuitive usage of the robot.

With different goals other than craniotomies, another miniature robot was applied in Minimally Invasive Surgeries (MIS). Moshe Shoham (160) and his group at the Technion - Israel Institute of Technology\(^\text{14}\) have developed a Miniature Robot for Surgical applications (MARS) with 6 degrees of freedom. Developed for MIS procedures, the imposed small working volume is fitting for a robot of this nature. This hexapod style mini robot was then used by Joskowicz from The Hebrew University of Jerusalem, for keyhole neurosurgery (88), and Shamir later experimented with the proposed method and proved it to be accurate, fast and robust, with an average accuracy of 1mm (158). The miniature robot does not consume too much space in the operating room and yet enables on-demand precise targeting and guidance. In addition this robot may be mounted directly on the patient's bone structure near the surgical site to avoid the need for patient immobilisation; registration is therefore maintained throughout the surgery.

Using laser surface scan registration with already the robot attached to the patient’s anatomy, the system matches the patient’s facial features with the CT / MRI data. This procedure establishes the common reference frame between the preoperative planning and the intraoperative situation. The actual robot targeting guide location is computed from the

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\(^\text{14}\) www.technion.ac.il
3D scan and compared to the predefined entry point and target location. The robot is then automatically positioned and locked in place so that the targeting guide axis coincides with the entry point / target axis.

![Figure 22 - MARS system concept mounted on phantom patient. Source: (88).](image)

PathFinder (Prosurgics\textsuperscript{15}, Cupertino, USA), is an image-guided six-axis robot that provides a stable, accurate tool position platform for neurosurgery (52). The PathFinder removes the need for a stereotactic frame and its associated calculations, employing instead for registration markers fixed to the skin of the patient and a Mayfield clamp to fix both the patient’s head and the robot’s base. The planning software automatically detects the markers on the CT and defines the coordinate system according to them. The surgeon selects the target(s) and entry point(s) and saves the plan. The plan file is loaded into the system and the robot arm sweeps a camera over the patient’s head to find the visually distinctive markers. By combining a series of frame grabs it estimates the location of the markers in robot coordinates and automatically registers itself to the surgical scene (46). A 2007 research report on the average application error accuracy on phantom patients was of 0.5 mm (51). This accuracy has been much improved since 2003 when it was stated as 2.7 mm (126). One of the disadvantages of the system is that the rigid fixation limits access to the patient’s head during surgery.

Prosurgics also offers the EndoAssist\textsuperscript{16}, an endoscopic robot manipulator used in minimally invasive thoracic and abdominal surgery.

In Radiosurgery, the CyberKnife\textsuperscript{\textregistered} System from Accuray\textsuperscript{17} (Stanford, USA) was designed to treat tumours anywhere in the body with a high degree of accuracy while using image guidance technology and a computer-controlled robot. The therapy for which it was designed does not involve invasive head or body frames to immobilise the patient; the robot swings the compact 6-MV X-Band linear accelerator around the patient in pre-

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\textsuperscript{15} Armstrong Healthcare changed its name to Prosurgics Ltd on September 28th, 2006.

\textsuperscript{16} www.prosurgics.com/prosurgics_endoassist.htm

\textsuperscript{17} www.accuray.com
planned paths, centred on the tumour while reducing the radiation exposure to healthy tissues. The registration between the intended target area inside the patient and the patient lying on the operating table does not rely on implant radiographic markers or fiducials. Instead, the CyberKnife system correlates live radiographic images with the preoperative CT or MRI scans in real time to determine patient and tumour position during the course of treatment. After given an initial position, the system continuously tracks the patient and tumour through the acquired ray emissions.

An estimated 35,000 patients to date have been treated with this system, and currently more than 50% of all CyberKnife procedures in the United States of America are extra-cranial. In the cranium, the announced accuracy by Accuray is 1.5mm but Inoue in 2006 (86) determined it to be 0.48 mm, with a tracking error of 0.22 mm and 0.2 degree rotational error.

Other state-of-the-art achievements in Medical Robotics include the small auto-cleavable robot presented by Schauer (152) and the KineMedic® a Robot for Medical Applications developed at DLR¹⁸ (Berlin, Germany) (44). The KineMedic is a custom-made universal robot for surgical interventions based on the DLR light-weight robot LBR-3 (43). This robot has been developed commissioned by BrainLAB AG (Munich, Germany), and its market release with European (CE) product certification was planned for 2007 under the name Vectorbot® (21). To date no further details have been disclosed, nor have clinical trials been published.
2.3 MEDICAL ROBOT COUPLING

Tool changers, grippers, connectors and coupling devices are designed for specific tasks and are common in industrial robotics (193). Most robot manufacturers already supply their solution for tool changers, as a multitude of specialized companies. Such tool changers are capable of providing electric power and signals, compressed air, fluids and hydraulics. They are normally designed for their working environments, but for medical applications extensive electronics hinders the ability to sterilize the device (177). Any part of the robot that can come into contact with the patient or which may contaminate the surgical field must be sterilized or covered with a sterile drape or plastic cover. The most common practice is the use of pre-sterilized bags and drapes covering most of the robot and the sterilization of the end-effector / instrument holder. Plasma, gas or soak sterilization is alternatively used if end-effectors contain motors or sensors; nevertheless research in new sensor and actuator technology would permit easier and cheaper sterilization, autoclaving, for example (171).

As more and more different surgical tools are employed with a single robotic system, the differences between the tool structures, as well as the interaction between tool and other components of the robotic system, become more pronounced (134). At the University of Washington a surgical tool rack system was developed (65). As part of the larger Traumapod Project (144), this subsystem enables robotic surgery without human assistance. It is capable of holding, accepting, and dispensing up to 14 tools to the DaVinci™ surgical robot. The tools remain in a sterilizable carousel in a compliant manner designed to accommodate misalignment during tool exchange, therefore eliminating the need to track the tool to be fetched. RFID equipment was as well integrated into the system so that tools could be inventoried and presented by function or serial number instead of rack position. The system is capable of presenting any stored tool in less than a second.

The necessity of identifying the surgical tool was also recognized by other researchers, and a solution patented by Intuitive Surgical, Inc. (Sunnyvale, USA) in 2002 (173) to be used with their systems. It simply includes a memory chip mounted on the tool. This chip can perform a number of functions when the tool is loaded on the tool manipulator: Firstly, the memory can provide a signal verifying that the tool is compatible with that particular robotic system. Secondly, it may identify the tool-type for the robotic system so that it can reconfigure its programming. Thirdly, the chip may indicate tool-specific information, including measured calibration offsets indicating a misalignment of the tool drive system, tool life data, etc.

Surgical tools are either sterilizable or are provided in hermetically sealed packages for use. In contrast, the complex surgical tool and end effector commercialised by Intuitive Surgical may be difficult and / or impossible to fully sterilize between procedures. Instead, a sterile drape will often cover at least a portion of the cart and robot structure to maintain the sterile environment around the patient. As tools will be removed and replaced repeatedly during many procedures, the tool holder could potentially be exposed to contamination if the interface directly engages the tool holder. To avoid contamination of the tool holder and possible cross contamination between patients, an adaptor for coupling

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19 Such as ATI Industrial Automation (Apex, USA), Maxbar Inc. (Houston, USA), SAS Automation (Xenia, USA), GRIP GmbH (Dortmund, Germany), etc.
the interface to the tool holder is also available (173). The tool changing procedure is executed by the surgical assistant.

In the specific case of needle placing robots or needle shaped tools during clinical procedures such as biopsy, radio frequency ablation, screw insertion or target drug delivery, this type of system does not couple with an already placed needle in the patient. Instead, the needle is placed manually by the surgeon once the robot is aiming at the target position, or there is a motor that slides the needle on an axis, as described by several researchers (160) (32) (17) (105).

In this case, sterilization is achieved with a simple sterile drape covering the robot arm, since the needle itself is sterilizable.

The industrial solutions presented strongly depend on a constricted, closed and predictable environment where the exact position of the tools is known. In such situation the robot is able to blindly guide itself to the correct tool, couple / decouple and continue its task (180).

In a situation where the position of the tool is unclear, either a human partner will manually attach the tool or a tracking system is required.

Burgner (23) (24) described a solution for this problem where both robot and patient-bound tool are tracked externally with passive optical markers.

The system has previous knowledge of the two constant transformations, between the end effector base and the robot’s flange, and between the tool and the end effector base in the coupled position (96).

The navigation system monitors both markers, determines a coupling axis, and then guides the robot arm automatically towards the tool. It is assumed that the surgical tool is rigidly attached to the patient during surgery (22), and that the optical navigation system maintains a line-of-sight to both markers.

The concept works in three phases: a manual phase where the user drags the robot to a nearby coupling position, a second semi-autonomous approximation phase, and a final automatic phase where the robot finishes the coupling while measuring the forces applied on the tool.

By “semi-autonomous”, the author intends to say that the robot is pushed forward towards the coupling device but is constrained in movement within a cone of the coupling axis.

The claimed system accuracy depends on several components, and is approximately 1mm, the larger source of error being the external optical tracking system using multiple markers and a large depth for small translations (186). Due to this tracking inaccuracy, a modified gripper from GRIP GmbH20 (Dortmund, Germany), was used. The original manual gripper G-MGW 050 was milled to a cone shaped edge to facilitate the connection between both pieces.

During the end phase where the robot moves automatically, forces applied on the end effector are measured constantly to determine a correct coupling of both pieces. If the forces overshoot a certain threshold, a collision is detected and the system comes to a halt. Effectively, the detected contact forces during the end phase help to guide the robot arm automatically to the final coupled position.
Sterility with this solution is carried out in both the end effector and the tool with passive markers while the robot arm is covered with a sterile cloth.

Currently, the robotic systems mentioned almost exclusively employ global maps for navigation purposes. This knowledge is grounded in information from external tracking sensors, which collect data from a large area and return it with associated position information (the data is embedded into a coordinate system, e.g. in optical tracking). Additional local information can also be collected from the immediate surroundings to help cope with uncertainty, measurement errors, and incompleteness of data (169).

To date, only one intrinsic camera-based solution has been described in a patent filled by Furness in 1992 (68). The camera is coupled to the robot as it detects the target and generates a position signal representing a current position of the robotic tool relative to the workspace. A system controller receives the position signal and computes the correct position based on the distance to the workspace, thus guiding the mechanical arm relative to tool and workspace. No mention of this device in a medical context was described.

The current state-of-the-art can further be increased with a medically safe interface or coupling mechanism which intuitively blends with existing robotic systems.

**2.4 DEVELOPED PROTOTYPE**

**2.4.1 SURGICAL TOOL**

This prototype was first designed for computer-aided orthognathic surgery, which is the discipline in CMF surgery concerned with the dentofacial skeleton (corrective surgery of the jaws) (142). In particular the maxilla was addressed and a solution to interact with this anatomy was thought of. However the design should be flexible enough to be applied to any rigid anatomical structure.

**2.4.1.1 PATIENT SIDE**

A flat mouth-piece with edges is used to wire with the brackets in the patient’s teeth. The surface of the area surrounded by the edges is dimpled with many indentations allowing pre-operative secure fixation of an imprint of the patient’s teeth, making this mouth-piece unique for each patient.
The size of the mouth-piece is relative to the size of the patient’s dentition. The spoon used to make the dental impressions will determine the size of the mouth-piece to use.

Before the patient undergoes surgery, a pre-surgical orthodontic treatment is frequently undertaken. During this phase the dentition is corrected with brackets, which stay until long after surgery. The brackets are subsequently used during surgery to wire the upper and lower jaw together; hence a strong adhesive is fundamental to sustain these forces (176) (167) (4). The designed tool for orthognathic surgery takes advantage of this situation and uses the brackets to wire and hold the maxilla for repositioning. This situation imposes that the bracket bonding is indeed strong and rigid to sustain the fixation it requires (79). In the case the brackets become loose during surgery, bone implanted screws can still be attached to the maxilla to wire the mouth-piece to the patient.

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21 http://trubyte.dentsply.com
2.4.1.2 ROBOT SIDE

On the opposite extremity of the surgical tool a visual target to track was placed, which consists of four circles inscribed on a 2D surface. These circles are painted with black non-reflective matt paint, producing a high-contrast optical marker (Figure 26). They have a known size and configuration which allows calculation of distance and orientation with an appropriate image processing algorithm.

Figure 26 - Two possible marker variations, white circles on a black background and black on a white background.

Additionally the head of the surgical tool has a circular crest with an outside thread which will be used to fix the tool with the robot (Figure 27). This connection is further explained in section 2.4.3.1 - Fixation rings.

Figure 27 - Surgical with coupling thread.
2.4.1.3 COMPLETE DESIGN

The surgical tool is built of aluminium as so to be lighter on the patient, while still maintaining its rigidity and functionality. The sterilization of the tool is therefore safeguarded, even with the usage of special high resistant colouring of the markers.

The surgical tool has a weight of 120g ± 2g, depending on the dental imprint.

In the following photo the design view of the surgical tool is depicted.

![Figure 28 - Design view of the mouth-piece, dimensions in millimetres.](image)

2.4.2 CAMERA HOUSING

The camera housing was designed to accommodate the selected camera and lenses. This situation imposed a few restrictions on the overall size of the prototype. The used camera is a C-mount Basler A101f with the outer dimensions of 62 x 62 x 49.5mm. The selected lens was a Cinegon 8mm F1.4, with dimensions of 37mm length and 51.75mm diameter.

Attached in front of the lenses is an LED illumination ring which adds 10mm to the length of the lenses. The full length of camera, lens and LED ring constrains the dimensions of the housing.

On the opening for the camera lens, there is a circular crest with an outside thread which will be used to fix the robot with the tool. This thread is the same size as the one on the surgical tool. The result is presented in the following technical drawings and photos.

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22 www.baslerweb.com
23 www.schneiderkreuznach.com
Figure 29 - Camera housing with camera, lens and light-source.

Figure 30 - Camera housing, without the camera and light-source.
2.4.2.1 CONNECTION WITH THE ROBOT FLANGE

The prototype device can be attached to the robot flange by any of sides of the camera housing, with the exception of the both front (lens) and back (camera itself).

Given that this application does not involve application of forces to the patient, but allows the intuitive guidance of the robot arm by pushing the robot in the desired direction, a FTS with a small force range and higher resolution was chosen. The company ATI Industrial Automation\(^\text{24}\) (Apex, USA) supplies the FTS model Gamma which was used in this application. In a FTS the applied forces and moments are subject to Newton’s third law of motion, shifting and rotating from one side inversely to the other one against the resistance of strain gauges with well-known stress-strain diagrams. These forces and moments can be computed and interpreted from the shift and/or twist applied by the surgeon. Nonetheless even in static situations without any application of forces on the design, the FTS still measures a certain residual force and torque due to the weight and position of the end effector itself. This constant bias needs to be compensated by software so as not to be interpreted as an intention of movement.

By providing this extra control and decision power, the surgeon is able to execute his functions faster, safer and more effectively. In Figure 31 we observe the camera housing attached to the FTS and robot’s flange.

The prototype was attached to both a modified Stäubli RX90 robot (Caspar system by Orto-Maquet (Rastatt, Germany)) as well as a KUKA LBR3 (KUKA Roboter GmbH, Augsburg, Germany) (Figure 31 and Figure 32).

The concept is indifferent to which robotic arm is used. Although previous developments used the RX90 there is a growing interest in the LBR3. The RX90 requires an extra FTS to program the force-control mode, whereas the LBR3 already has a gravity-compensation mode from its embedded force-torque sensors. Additionally, the smaller footprint on the surgery room of the LBR3 is of high interest to both the surgeons and engineers. The LBR3 has increased flexibility and overall sensory equipment dedicated to the sensitive area of human interaction. This brings to this robotic assisted orthognathic surgery a worthy benefit that triggered the interest of the research.

\(^{24}\) http://www.ati-ia.com/
Figure 31 - From the left to the right: gripper for end effector switch, force-torque sensor, camera housing with exposed light-source.

Figure 32 - Prototype attached to the LBR3.
In the case of the RX90 between the housing and the robot flange the Force-Torque Sensor is placed. This FTS has the purpose of allowing the surgeon to grab the camera housing and guide the robot arm intuitively towards and from the surgical tool. The gripper between the robot flange and end effector has the purpose of facilitating end effector change between robot arms.

With the LBR3 there was no need to connect it to an additional FTS since this model already contains force sensing in all its joints.

2.4.3 IN-BETWEEN PIECE

The surgical tool is separated from the end effector by a circular in-between piece, with orientation edges and fixation rings. The fixation rings have their complementary lock part located in both tool and in the end effector.

The hollow centre of the piece is occupied by a glass window, providing isolation between the sterile area and the non-sterile while maintaining an open line of sight for the camera. Consequently, this piece has the function of providing the sterile interface between the mouth-piece and the robot’s end effector.

2.4.3.1 FIXATION RINGS

For the requirement of exact matching between the surgical tool and the robot, two indentations on coupling surfaces provide this precise orientation. The two ends fit perfectly with the crests found on both the surgical tool as well as in the camera housing allow only two possible connections (Figure 33). Either side of this tool can be placed to the camera or the tool, since they are exact matches and do not affect the expected accuracy.

The two edges allow the exact orientation of the tool, avoiding any slip or rotation of the tool once coupled. The placement of these two edges gives the impression that the tool can be placed with 180° of difference, but this situation is impracticable since that would make the maxilla of the patient to be higher than the prototype and the robot arm under the chin. Thus only one connection is possible.

Figure 33 - Left: In-between piece with glass window. Right: Detail of the orientation edge with fixation ring.
2.4.3.2 STERILITY

On the outside of this piece it is possible to fix a sterile drape which will cover the robot arm (Figure 34). All material that needs to be sterilized is made of steel or glass and can undergo any type of sterilization process.

![Figure 34 - Placement of the sterile drape on the laboratory setup.](image)

This piece then provided the sterile interface between the robot arm and the patient-bound tool (Figure 35).

![Figure 35 - Sterile separation scheme.](image)
2.4.4 **CONNECTION BETWEEN ALL COMPONENTS**

The prototype was produced with a mechanical tolerance between pieces of 0.02mm, which allowed the easy connection between the coupling pieces, while maintaining the required mechanical stability. The three pieces are connected by rotating the fixation rings (Figure 36).

![Figure 36 - Schematic of all three components and their connections. On top the separated pieces, below the assembled design.](image)

In Appendix A are presented the complete technical drawings of the developed prototype.

2.4.4.1 **LAYOUT OF THE OR**

The proposed system for orthognathic surgery (22) is based on a Stäubli RX90 robot and an optical tracking system. The selected robot weighs 310Kg, it is 140cm high, 42.4 cm wide and approximately 70cm long (166), including the wheeled platform on which it is mounted on. With its relatively large dimensions, the robot leaves a large footprint on the already overcrowded operating room (Figure 37: Left)
A light-weight robot such as the LBR3 requires a much smaller amount of space (Figure 37: Right). The LBR weighs 14Kg and has dimensions slightly larger than a human arm. Although the flexibility of the LBR3 is higher than that of the RX90, the stability of the robot arm in holding the position of the maxilla in position could be questioned. This question is further answered in the chapter 6 - Results.

In either case the prototype here presented behaves in similar fashion regardless of the chosen robot to perform the robotic assisted orthognathic surgery.

2.4.4.2 PREPARATION FOR SURGERY

Before surgery, the camera housing is fixed to the extremity of the robot arm, building the basic end effector (Figure 32). The OR assistant will bring a sterilized in-between piece with the sterile cloth to the robot, attaching one of the ends to the camera housing and securing it by rotating the fixation ring (Figure 38). The sterile drape is then pulled over the robot covering it completely and isolating it from the OR (Figure 39). Thanks to this method the robot is completely sterile and separated from the patient.
Figure 38 - Top left: Sterile assistant brings the in-between piece to the robot arm. Top right: the non-sterile assistant fixes the ring on the non-sterile area. Bottom left: The sterile assistant inverts the sterile drape over the robot arm. Bottom right: Stretching the sterile cloth over the robot arm.
During surgery, the mouth-piece is attached to the patient’s maxilla (Figure 40, right), following the proposed workflow (Chapter 1 - Table 1). The dental impressions previously acquired correspond exactly to the patient’s dentition and the mouth-piece is fixed using a metal wire between the edges and the brackets.
The surgeon will bring the robot arm over the patient in force-control mode, and as soon as the camera sees the target, it corrects its movement towards it. The direction of the applied force will determine if the surgeon wishes to couple or decouple the robot arm, moving the robot arm to or from the target, but always on the coupling axis. The force-control mode operates in a simple intuitive way, paving the path towards the semi-automatic coupling.

When the system does not recognize any target, the surgeon is able to manoeuvre the robot freely and to position it in a comfortable way.

The first connection with the patient-bound tool is the registration process, where the system will identify the relative position of the patient’s maxilla before osteotomization as the starting point of the transformation. Once the system is correctly positioned, the surgeon then only needs to rotate the exposed fixation ring to complete the coupling procedure (Figure 41).

![Figure 41 - Coupling with the surgical tool and fixation. Top: Robot coupled without fixation. Bottom: Fixation ring rotated and robot rigidly attached to the surgical tool.](image)

Once the patient position is registered, the uncoupling procedure is the same: Rotate the fixation rings, confirm in the software that decoupling is to be performed, and push the robot away (semi-automatic). In the automatic mode the surgeon simply needs to confirm in the software and the robot will move away by itself. Any robotic movement is only performed when a control button is the kept pressed. This ensures higher safety since the operator can quickly release the switch and the robot will come to an immediate halt.
For the second coupling time, the robot will couple with a loose maxilla. Given the 120g of weight of the surgical tool it is suggested that the doctor holds the tool to avoid excessive weight on the osteotomized bone segment. The final coupled position is shown in Figure 42.

Figure 42 - Phantom attached to the robot with the mouth-piece.
2.4.5 PHANTOM

To test the prototype under realistic conditions a plastic skull with the Le Fort I Osteotomy was manufactured (Figure 43). The phantom simulates the soft tissue still held to the maxilla after the maxillary downfracture with elastic rubbers and small hooks (Figure 44). The placed brackets allow the fixation to the mouth-piece as proposed.

Figure 43 - Phantom patient. Left with maxilla in the wrong position. Right with maxilla in the correct position.

Figure 44 - Phantom skull with loose maxilla, brackets and rubber bands holding the maxilla.
2.4.6 PC CONTROLLER AND REMAINING HARDWARE ASPECTS

The coupling procedure is done in the same PC that controls the planning transfer tasks of the new orthognathic surgery approach. Additionally it requires only a USB and a firewire port for managing the following aspects:

- Camera frame capture.
- Light source control.
- Image processing interpretation.
- Force-Torque interpretation.
- Robot controller communication.
- Graphical user interface with the coupling information.

The LED ring light source is controlled by an “off-the-shelf” USB interface board. The Velleman25 (Gavere, Belgium) K8055 interface board has 5 digital input channels and 8 digital output channels, but only one of the digital output channels was used to control the light source (Figure 45). Additionally, custom made electronics was added to give the right amount of electrical power to the LED’s as well as an off-line light switch for debugging purposes.

All communication routines are contained in a Dynamic Link Library (DLL) for Windows platforms as well as an open source library for Linux. Although this application was restricted in function to on and off, a future interest in this board would be to control dynamically the amount of light using software.

Figure 45 - K8055 USB interface board from Velleman (Gavere, Belgium), with power supply control.

25 www.velleman.be
2.5 IMAGE PROCESSING AND INTERPRETATION

2.5.1 PHOTOGRAMMETRY AND RELATED WORK

Several approaches to optical 3D space reconstruction have been used so far. Most image-based methods are passive, including visual hull, stereo-triangulation, shape from shading, shape from photo-consistency, voxel colouring, space carving (103), as described by several researchers (47) (64) (111, 15). Active photogrammetry solutions are used for mobile robot navigation, and are able to reconstruct maps and paths from visual information (63) (106) (41).

Some of these image processing and interpretation techniques can be used in this simple tracking and coupling situation, however, having the tracking algorithm running in a background thread together with another, possibly complex application imposes a fast (real-time) solution, reliable and with high enough accuracy.

Estaña presented a highly accurate visual coupling technique for micro-robots based on moiré-patterns, but unfortunately it lacks the 3D depth information. Estaña’s moiré approach only allows X and Y guidance and coupling (57) (56).

Similar to the concept used in this thesis, Zhang’s (195) depth-from-size approach has an accuracy problem and was designed for measuring larger displacements (over 1 meter). By definition, in close-range photogrammetry the distance from the camera to the object of interest is between 1 to 300 meters (111). In this application the distance is especially close; the tracked area is in the range of 8 to 3cm as it is required for a successful coupling.

The reduction of a three-dimensional object to a two-dimensional image implies a loss of information. Object areas which are not visible in the image cannot be reconstructed from it. This not only includes hidden parts of the tracked target but also regions which can not be recognized due to lack of contrast or limiting size. Circular flat objects in 3D are viewed as ellipses on a 2D image plane; nonetheless, their 3D positions can be computed from their projections (91). More research is undergoing with monocular systems to calculate depth, position and orientation (16). Saxena’s approach to depth estimation consists of supervised learning in which the algorithm collects a training set of images and their corresponding ground truths (151) (150) (149). It aims to improve the performance of stereovision and creating large scale 3D models out of a small number of images. For very close photogrammetry these approaches have not been tested.

The whole photogrammetry concept used in this project was programmed and tested in C++ and with use of OpenCV’s\(^{26}\) Computer Vision libraries, supported by Willow Garage (Menlo Park, USA).

\(^{26}\) http://opencv.willowgarage.com/
2.5.2 CAMERA MODEL AND CALIBRATION ISSUES

A real and practical photogrammetric camera will differ from the traditional pinhole camera model (Figure 46). The necessity of using a relatively complex objective lens, a camera box with an aperture which is not pinhole and the fact that the target will not be parallel to the image plane gives rise to departures from the ideal linear image geometry (111).

![Figure 46 - Pinhole camera model.](image)

Equation 1  \[ m = \frac{h}{c} = \frac{X}{x'} \] Where m is the scale factor of the variables presented in Figure 46.

In fact, practical observations note that with the change of depth, h, the scale factor, m, is not constant. For this reason several calibration and undistortion algorithms have been developed and are now common practice (59) (83) (174). Depending on the accuracy requirements of each photogrammetry application, the camera model is typically based on either orthographic or perspective projection. Orthographic projection is the roughest approximation assuming the objects in 3D space to be orthogonally projected on to the image plane. It is more suitable for vision applications where the accuracy requirements of the geometric projections are lower. Assuming linearity, it provides a simpler and computationally less expensive solution than perspective projection. On the other hand, for 3D motion estimation and reconstruction problems, perspective projection gives a nonlinear form of mapping, which is quite accurate for high quality camera systems. For off-the-shelf systems, the perspective projection model often needs to be augmented with a lens distortion model (83).

For the present application, a first attempt to calibrate the camera was done to test the necessity of undistortion and to measure the difference between distorted and undistorted frames. OpenCV includes a camera calibration toolkit based on Tsai’s calibration algorithm (174), as well as an undistortion function capable of near real-time image capture and undistortion. With these libraries, a small application was programmed under Windows XP 32bit environment to acquire frames in real-time, calculate the distortion and all required parameters (Figure 47).
The lens used in this prototype is a Cinegon 8mm F1.4\textsuperscript{27}, which has an extremely low distortion level. The low amount of distortion this lens produces is quickly perceived when comparing the original captured frames with the calibrated ones (Figure 48). The calculated camera parameters were then imported into the image processing application and the undistorted frames were compared with the original frames.

The difference of the circle’s width and height was measured. The features were displaced between frames in the area of 1 to 0.3 pixels, averaging in 0.73 pixels. This is a percentage

\textsuperscript{27} www.schneiderkreuznach.com
difference below 0.42% of the circle’s width / height and 0.82% in area. The sample values are presented in Figure 49.

![Percentage difference between frames](image)

**Figure 49** - Comparative graphic of the percentage difference between original and undistorted frames. The horizontal axis contains the sample number, the vertical axis presents the percentage difference between calibrated and non-calibrated frames.

This difference can thus be ignored since the error it produces is tolerable.

### 2.5.2.1 TARGET TRACKING CALIBRATION

The prototype was designed with the intention that all pieces fit perfectly when coupled and the image sensor is horizontally and vertically aligned with the target plane, however due to hardware restrictions and mechanical finish of the prototype, a slight offset of the target regarding the centre of the image plane is observed (Figure 50).

![Filtered frame vs Processed frame](image)

**Figure 50** - Coupling successful: Target centre and orientation offset.

The centre of the target and rotation offset can be calculated when the target is coupled. The values obtained can then be inserted in the image processing and kept as bias.
constants. When calculating the amount of displacement necessary to couple with the
target, the constant bias will provide the necessary information to correctly couple the robot.

2.5.2.2 FORCE TORQUE SENSOR CALIBRATION

When using the Stäubli RX90 a Force Torque Sensor (FTS) is placed on the robot flange to
program the force control mode. In order to acquire correct values from the FTS, the
sensor must first be calibrated. The weight and position of the end effector causes a
constant force on the sensor as it pushes down towards the centre of the earth. With this
force constantly applied, the sensor will detect residual force and moment. This constant
bias needs to be compensated by software so as not to be interpreted as an intention of
movement.

The applied forces (f) and moments (m) can be calculated by a simple matrix
multiplication, Equation 2:

\[
\begin{pmatrix} f \\ m \end{pmatrix} = A \cdot u
\]

In this context, both f and m are three element vectors for force and moment, and A is a
6X6 invariant matrix supplied by the manufacturer. The produced output u consists of six
values, being respectively three for the force and three for the moment. The measured
voltage \(u_M\) is composed of two elements: the strain applied, u, and the bias, \(u_B\), so that \(u_M = u + u_B\). By substitution and rewriting Equation 2 it is possible to isolate the bias \(u_B\):

\[
\begin{pmatrix} f \\ m \end{pmatrix} = A \cdot (u_M - u_B)
\]

\[
\begin{pmatrix} f \\ m \end{pmatrix} = A \cdot u_M - A \cdot u_B
\]

\[
\begin{pmatrix} f \\ m \end{pmatrix} = \begin{pmatrix} f_M \\ m_M \end{pmatrix} - \begin{pmatrix} f_B \\ m_B \end{pmatrix}
\]

This bias value \(u_B\), consisting of both \(f_B\) and \(m_B\), must be calculated prior to use. Norm
dictates that \(f_B\) and \(m_B\) are determined and aligned so that all six values are positions
parallel to the force of gravity (73).

As the end effector does not change mass throughout the procedure one can assume that
there is a constant weight of the end effector pulling down towards the centre of the earth,
regardless of the sensor position. The norm of the force (weight) being constant one can
easily determine the 3 components of the bias by averaging measurements (Equation 4).

\[
f_{M,i} = f_i + f_{B,i}
\]

By definition, moment is the applied force multiplied by a radius, which means that the dot
product of a three-dimensional force and its momentum is zero. Substituting m by \(m_M - m_B\)
results in:

\[
f \cdot (m_M - m_B) = 0
\]
By solving the equation system presented by Equation 4 and Equation 5 with measured values from the FTS it is possible to calculate the bias.

In the case of the LBR3 with integrated FTS in each joint, it is the robot controller’s task to calculate this bias. One must simply define the weight and centre of mass of the end effector on the controller and this configuration is stored and calculated internally when required.

2.5.3 TOOL TRACKING

2.5.3.1 MARKER CONFIGURATION

The visual target consists of four circles inscribed on a 2D surface. These circles are painted with black non-reflective matt paint, producing a high-contrast optical tracking target. The larger central circle is 18mm diameter while the smaller ones are 8mm (Figure 51).

![Figure 51 - Marker size and configuration.](image)

These features are present in the software by means of system constants. However the importance of these values is relative only to the depth adaptation curve.

Whether the circles are black on a white background or white on a black background poses no difference to the image processing algorithm which looks for circle’s edges. A high contrast is the only requirement.

2.5.3.2 REGION-OF-INTEREST

As the camera captures an area bigger than necessary, a Region-of-Interest (ROI) was defined which crops the unnecessary pixels. This approach is common in image processing and lowers computational costs. This ROI is updated with the position of the detected features and speeds up the process by ignoring features outside its area.

The full frame size is stored in an OpenCV structure. The ROI where the target was last detected plus an extra margin is kept in a separate variable.

When the target is detected a specific function will optimize this ROI to an area and location dependent on the position and size of the visible markers (Figure 52).
OpenCV allows ROIs of rectangular shape only (Figure 52), however in all the acquired figures from the camera the light source is visible as well. The Region-Of-Interest in this application is in fact circular. To avoid misjudging the small LEDs as ellipses which happen to fall within the rectangular ROI, a particular constant is initially calculated. The constant acceptance Radius dictates how far away from the centre of the image frame is an element allowed to be, in order to be considered part of the target. This is computationally different than that of the ROI, and it complements the ROI in that matter.

When analysing the contours found within the rectangular ROI, if the ellipse which fits to the detected contour has the centre outside the acceptance radius, it does not belong to the target and the analysis proceeds to the next contour.

2.5.3.3 ADAPTIVE THRESHOLD AND CONTRAST ENHANCER

To accurately isolate the circles from the background a custom-made filter was designed. The histogram of the pixels inside the ROI is calculated and a contrast S-curve is fit to its values.

Because of the slow speed at which the robot moves, and the independent light-source, there is little change in luminosity between consequent frames. It was determined that a refresh rate of approximately one Hertz is more than adequate to maintain a clear segmentation of the circles.

Mathematically the filter simply stretches the lower bound of the histogram to 0 (deep black) and the higher to 255 (pure white), the luminance values of the prominent feature are spread in an S-curve (Equation 6).
Equation 6

\[
\sum_{i=1}^{255} \frac{255}{1 + \left( \frac{\max_{idx} + 10 - i}{20} \right)}
\]

max_idx is the index number of the prominent feature
i is the running variable in the histogram from 1 to 255

Equation 6 produces a curve where the values of the histogram are 0 shortly until the finding of the largest histogram peak and in an S-like curve grows to 255 after the peak. Figure 53 depicts this function assuming a max_idx of 100.

![Figure 53 - S-curve graph for a feature at index 100. The horizontal axis contains the input luminosity values, and the vertical the output values. This function smoothly blackens or whitens features too far apart from the central feature.](image)

OpenCV includes a histogram calculation function which supplies the minimum and maximum index values, allowing a quick implementation of the concept. The filter is applied to the image using a Look-Up-Table (LUT). The luminosity information is applied to the image and additionally a 3x3 soften blur is performed.

2.5.3.4 ELLIPSE FITTING AND FEATURE DETECTION

Once the frame is filtered the image processing will detect contours of the features perceived in the ROI and evaluate if they belong to the target or not. This is done firstly with the application of a Canny edge detector.

Because the Canny filter employs a first derivative Gaussian filtering, it is susceptible to noise present on unprocessed image data, therefore it is common practice to previously soften / blur the image frame. The softening has already been applied when calculating the contrast enhancement (2.5.3.3 - Adaptive threshold and contrast enhancer). The result is a slightly blurred version (with a 3x3 softening) of the original image which is more noise resistant.

The Canny filter was selected instead of a Sobel filter, Robert Cross or a simple adaptive threshold due to its soft edge detection characteristics. Since the target will be at an uncertain distance from the camera and the camera has a fixed focus point, the target will be often blurred. Under laboratory conditions this approach proved to be more reliable and consistent.
The next step after a successful segmentation is the storage of the edge contours in an OpenCV structure specific for point sequences. This allows fast access between pixel points of the detected contours. While searching each sequence of points belonging to the same contour, a few tests are performed:

1. Is the area of the detected feature larger than a specific number? This condition eliminates small error features, such as large noise particles or dust on the lenses.

2. Is the centre of the feature outside the acceptance radius? Eliminates features outside the area of interest.

3. Is the fitting error of the ellipse higher than a certain threshold? Eliminates structures which are not ellipses.

The following flowchart represents this procedure:
As ellipses which match the search criteria are found, their information is stored in four specific variables in the order that they are found. Subsequently these four ellipses need to be organized in a meaningful sequence. The identification of these ellipses is fundamental for the correct calculation of the coupling axis.
Only the larger central circle is easy to identify due to its size, however the three smaller circles are stored in the order in which they were found. If the target is rotated the identification of the circles is not straightforward as claiming left or right of the central circle. To correctly identify the circles (Figure 55) an algorithm was introduced which relates the relative distances between the circle centres.

The algorithm compares the relative distances between the three circle’s centres. Circles 1 and 3 will always have a higher distance between each other than with number 2. This geometric condition conditions allow the isolation of circle number 2. Afterwards the relative position of 3 and 1 is verified, by comparing which of the two remaining circles one is more to the left. This algorithm although effective has the limitation of allowing a maximum target rotation of 90° in either direction. However that poses no concern since mechanical restrictions in the coupling device render unpractical to rotate the end effector more than 90°. Figure 56 illustrates this algorithm.

Figure 55 - Circles correctly identified on the target plane.

Figure 56 - Flowchart of circle identification and sorting.
2.5.3.5 CONTINUOUS FEATURE TRACKING AND WORKING IN REAL TIME

A secondary goal is to provide a solution which is intuitive. This can only be achieved if the image processing algorithm is fast enough to provide the required information to the robot control system.

The Basler A101f has a frame-rate of 15 frames per second. As a result a first separation between the different software modules is done with the frame capture thread. This specific thread is responsible for capturing a frame, calculate the required image information and supply it to the remaining system modules.

At a higher frequency and independent from the image processing, the robot controller thread will check the distance information and move accordingly.

With the camera placed on the coupling axis, continuous updated target information is available throughout the robotic approach and coupling procedure. Although the image processing thread has a lower frame rate, the information is continuously available allowing corrections in robotic movement and guidance, particularly when the target is not fixed in space.

2.5.4 DEPTH CALCULATION

The concept pursued in this thesis for depth calculation is simply uses a quadratic curve which relates the circles perceived area and the effective distance at which the target is, making this solution a nonlinear mapping of the coupling axis (178).

To determine the effective distance in mm between the image plane and the target, a Platinum FaroArm with a known inaccuracy of 0.013mm (58) was used. The image processing segmented the circles and provided the basis for the comparative measurements. With small displacements and maintaining the image plane parallel to the target plane, several points at different distances from the target were collected and a trend line was calculated correlating the circle’s area with the distance to the target. In Figure 57 this relationship is illustrated for the larger central circle. In Figure 58 the remaining smaller three circles are depicted with the same intention.

\[ y = 0.00000000149234111x^2 - 0.0007911317671372x + 105.9269544957600000 \\
R^2 = 0.9948570957306900 \\
\]

![Figure 57 - Relationship between circle area in pixel and distance to the target in millimetres.](www.faro.com)
Figure 58 - Relationship between the smaller circle's areas in pixel and distance to the target in millimetres.

These quadratic trend lines are the basis for the depth calculation. Inserted in the code they provide the depth information for each individual ellipse. Together with the relative information of X and Y of each ellipse centre, we have effectively four 3D points in space which lie on the same plane.

2.5.4.1 CALCULATE COUPLING AXIS AND OTHER RELEVANT INFORMATION

In order to calculate the coupling axis it is required to convert the distance information acquired from the circles into the same dimensions. The chosen approach was first to convert the XY plane information to millimetres using Equation 7, followed by the depth approach first described above, which returns values already in millimetres.

Equation 7

\[
\text{relationship mm px} = \frac{\text{actual perimeter (mm)}}{\text{perceived perimeter (px)}}
\]

From the segmented ellipses we extract three relevant points to calculate the Normal vector of the target plane. Each ellipse provides the centre X and Y as well as the distance Z from its perceived size (Equation 8).
Equation 8

Point 1 [X] = Circle 1 position X \( \text{relationship px mm} \)
Point 1 [Y] = Circle 1 position Y \( \text{relationship px mm} \)
Point 1 [Z] = \( 1.27760913 \times (\text{Area Circle 1}^2 - 2.40376494569 \times \text{Area Circle 1\textsuperscript{3}} + 114.53153374) \)

Point 2 [X] = Circle 2 position X \( \text{relationship px mm} \)
Point 2 [Y] = Circle 2 position Y \( \text{relationship px mm} \)
Point 2 [Z] = \( 1.27760913 \times (\text{Area Circle 2}^2 - 2.40376494569 \times \text{Area Circle 2\textsuperscript{3}} + 114.53153375) \)

Point 3 [X] = Circle 3 position X \( \text{relationship px mm} \)
Point 3 [Y] = Circle 3 position Y \( \text{relationship px mm} \)
Point 3 [Z] = \( 1.27760913 \times (\text{Area Circle 3}^2 - 2.40376494569 \times \text{Area Circle 3\textsuperscript{3}} + 114.53153375) \)

From these three 3D points the normal vector of the target plane is calculated (Equation 9).

Equation 9

\[
\begin{align*}
\text{Normal X} &= \frac{(\text{Point2}[Y] - \text{Point1}[Y]) (\text{Point3}[Z] - \text{Point1}[Z]) - (\text{Point2}[Z] - \text{Point1}[Z]) (\text{Point3}[Y] - \text{Point1}[Y])}{\text{length}} \\
\text{Normal Y} &= \frac{(\text{Point2}[Z] - \text{Point1}[Z]) (\text{Point3}[X] - \text{Point1}[X]) - (\text{Point2}[X] - \text{Point1}[X]) (\text{Point3}[Z] - \text{Point1}[Z])}{\text{length}} \\
\text{Normal Z} &= \frac{(\text{Point2}[X] - \text{Point1}[X]) (\text{Point3}[Y] - \text{Point1}[Y]) - (\text{Point2}[Y] - \text{Point1}[Y]) (\text{Point3}[X] - \text{Point1}[X])}{\text{length}}
\end{align*}
\]

The next step is to calculate a point on the target as the centre and classify it as the starting point from where the normal vector starts (Equation 10). With this procedure the coupling axis is determined and the point to where the robot arm should move to as well.

Equation 10

\[
\begin{align*}
\text{Target}[X] &= (\text{Target} X - \text{Central circle position} X \text{relationship px mm}) \\
\text{Target}[Y] &= (\text{Target} Y - \text{Central circle position} Y \text{relationship px mm}) \\
\text{Target}[Z] &= \frac{1.4923411 \times (\text{Area Central Circle}\textsuperscript{2} - 7.911317671372 \times \text{Area Central Circle} + 105.9269545)}{\text{length}}
\end{align*}
\]

Where Target X and Target Y are values obtained with the target calibration procedure.

The other geometric information which is calculated is the co-planar angle. This angle simply relates how much the robot arm should rotate within the coupling axis in order to perform an exact coupling of robot and tool.

A horizontal 2D line is fitted through the centre of circles 1, 3 and the central circle. Horizontally all these circles are aligned. A second line is calculated passing through the central circle and circle 2. Likewise these two circles are vertically aligned. The two lines are perpendicular to each other; therefore two angles can be measured to the horizontal image frame for reference (Equation 11).

Equation 11

\[
\begin{align*}
\text{Angle1} &= 90 - \arctan \left( \frac{\text{Vertical line Y px}}{\text{Vertical line X px}} \right) \times \frac{180}{\pi} \\
\text{Angle2} &= \arctan \left( \frac{\text{Horizontal line Y px}}{\text{Horizontal line X px}} \right) \times \frac{180}{\pi}
\end{align*}
\]
The two angles are then averaged and provide the coplanar rotation angle needed to perfectly align the target and the camera. The yaw and pitch angles are calculated simply by the size difference of the three smaller circles.

2.5.5 REFERENCE FRAMES AND COORDINATE SYSTEMS

The robot controller receives commands composed by 3D coordinates and angles. These coordinates can be relative to the world coordinate system or tool. This allows developers to simply inform the controller that it should move one millimetre forward in the Y direction of the tool / end effector, without requiring calculation of complex inverse kinematics.

The image processing on the other hand provides relative position information. The camera has its own coordinate system with the origin located on the first top-left pixel of the image plane. The X axis grows in the width direction and Y in the height. The Z axis is simply the depth growing forward from the optical axis (Figure 59).

As observed in the schematic above, with both the Stäubli RX90 and the KUKA LBR3 robots, the camera housing was placed in the end effectors flange so that the coordinate system is parallel to the robot’s flange. This allowed the direct correlation of the coordinate axis: X axis in the camera coordinate system corresponds to the Z axis in the robots flange, the Z of the camera to the Y of the tool and Y of the camera to the X of the tool coordinate system. This can be easily expressed by the rotation matrix in Equation 12 (36).

Figure 59 - Reference frames in the system.
Equation 12

$$\begin{bmatrix}
-1 & 0 & 0 \\
0 & 0 & -1 \\
0 & -1 & 0
\end{bmatrix}$$

This rotation of origins is simple to implement, as it only shifts the values of the direction of movement (36). The slight translation of origins is as well constant, but does not require computation since the camera provides relative positioning within that reference frame.

In the case of the RX90, the controller software does not warn that a specific joint is almost at its rotation limit. If a singularity is reached when trying to follow the surgeons commands, the surgeon simply needs to pull the robot arm away in the same direction it was coming from and try another approach.

The LBR3 has 7 Degrees-Of-Freedom (DOF), and although in practice one is not used and would have the same problem as the RX90, the LBR3 controller has built-in a singularity avoidance library (191). This allows a higher freedom to the surgeon to manoeuvre the robot arm, since the controller will look to avoid singularities by himself.

### 2.5.6 FORCE TORQUE SENSOR DATA INTERPRETATION

The goal of intuitive usage is achieved by guiding the robot arm in force control mode. The forces applied to the FTS indicate the direction intended for movement and the user is able to position the end effector to a gross start position. As soon as the target is identified and its relative position is calculated, all robot movement is constrained along a path that leads to the correct coupling. The user can still manoeuvre the robot arm towards and from the target, but all forces which are applied perpendicular to the coupling axis are ignored. This is the semi-automatic coupling concept.

For automatic coupling, as soon as the target is identified, the robot moves slowly towards it disregarding the FTS information, with other words, the user.

The behaviour of forces was first modelled by Newton in his third law of motion: *To every action there is always opposed an equal reaction; or, the mutual action of two bodies upon each other are always equal, and directed to contrary parts.* The transducer of the FTS reacts to applied forces and torques using Newton’s third law. Internally the force applied to the transducer flexes three symmetrically placed beams using Hooke’s law:

Equation 13

$$\text{Stress applied to the beam} = \text{Elasticity modulus of the beam} \cdot \text{Strain applied to the beam}$$

Semiconductor strain gauges are attached to the beams and are electrically considered strain-sensitive resistors. The resistance of the strain gauges change as strain is applied to the beams. The FTS will then produce six voltages across its sensing elements which with the help of an internal Wheatstone bridge is linearized (8). Still hysteresis is normal with these sensors and the chosen model from ATI-IA is no exception (73).

When implementing the concept in this application, a known condition is that the FTS is placed directly at the robot’s flange and that the forces and moments applied to the end effector are aligned with the axis of the robot’s flange and only affected by constants (Figure 59).
A convention was made and 1N applied to the end effector results in 0.9 mm movement in the direction of the force, and 1 Nm torque in 1.8° movement.

The LBR3 does not require the use of an external FTS for the force control mode. This robot platform already includes a FTS in each of its seven joints, and the controller already supplies a gravity compensating mode which implements this concept.

### 2.5.7 GRAPHICS USER INTERFACE

The Graphics User Interface (GUI) was designed to present the relevant information to the surgeon without too much detail, or unnecessary confirmations (Figure 60). Some options can be set at the beginning of the procedure, and afterwards everything can be controlled with the robot switch and dragging the robot arm.

Only the decoupling procedure requires confirmation on the computer itself that all the pieces have been correctly detached and that it is safe to move the robot arm away from the tool.

![Figure 60 - Screenshots of the coupling software in operation.](image)

The 4 buttons offer the surgeon the following functions:

1. **Start tracking.** It identifies if the target is visible or not.
2. **Uncouple.** This button is only active upon successful coupling. It orders the robot to move away from the tool. It will require a second confirmation that everything has been released and it is safe to move away. This is done with a pop-up window.
3. **Start coupling** button is active after the tracking system has been started. It enables the system to initiate the active search for the coupled status as soon as ever the tool is visible while moving the robot. If the intention is the visualization of tracking information only, it is not required to press this button.
4. The **stop** button is active as soon as the tracking starts. This button is used to terminate coupling and additionally serves as an emergency stop button.
Green and red lights bid confirmation and negation of the presented information. The supplied information is:

1. If the robot is coupled.
2. If the robot is moving.
3. If the communication with the robot is active.
4. If the communication with the Force Torque Sensor is active.
5. If the target is visible.

The surgeon can also opt between which view of the camera he prefers if any, as well as the type of coupling intended: Automatic or Semi-Automatic.

The screen is complete with numeric information relating the amount of force being exerted in the force torque sensor, the distance at which the target is, how much rotation is necessary on the coupling axis and the control frame rate.

### 2.6 EXPERIMENTAL SECTION

#### 2.6.1 TRACKING ACCURACY AND PATH OPTIMIZATION

In order to determine the tracking accuracy of this method the following experiment was conducted:

The robot is moved to a random position in space. From this position the camera is able to see the target, and with the subsequent image processing is able to calculate the 3D position and orientation of the target. During this experiment the robot was moved to 221 different positions and orientations within the working volume of the arm, and where the image capture was possible. I.e. the position of the arm was not behind the tool (Figure 61).
Figure 61 - Tracking volume expressed as wireframe. This tracking volume extends from the centre of the tool to a distance where the markers are perceived too small on the image sensor.

The real physical distance between the target point and the camera was provided by the FaroArm\textsuperscript{29} and compared with the distances indicated by the image processing calculation (Figure 62).

\textsuperscript{29} The FaroArm has a known inaccuracy of 0.013mm, available from: http://measuring-arms.faro.com/distri/start/
Four points on the tool were picked as reference and considered immobile throughout the measuring procedure. Six additional points in the camera housing were picked for tracking the movement of the camera.

In order to calculate the tracking errors, reference planes and lines were defined (Figure 63). One plane is parallel to the image plane, defined by three points on the surface of the camera housing. Another perpendicular plane was defined from three other points on the top of the camera housing. And finally the target plane defined by four points on the surface of the tool, plus the target centre defined by the crossing of two lines.

From the collected 221 points in space the 10 aforementioned points were measured and a set of measuring errors calculated; See Appendix B to Appendix D.

The calculated errors are presented in the results section as a cumulative frequency graphic (37) as well as 3D special distribution within the tracking volume.

### 2.6.2 COORDINATE SYSTEM IDENTIFICATION FOR COUPLING EXPERIMENTS

A Force-Torque Sensor was attached to the surgical tool where as the teeth of the patient would be during surgery and arbitrary orthogonal directions defined (Figure 64 - Left). The robot tool coordinate system was also identified and kept in relationship to the tool throughout the whole set of experiments. The FTS axis orientation was arbitrarily chosen, but rotated in a way that would be grossly aligned with outputs Fx, Fy, and Fz.

The robot tool coordinate system and its rotation angles together with the FTS definition of the forces are later referred along with the experimental results.
The coupled position of the end effector and tool is taken as the origin (zero) for all measurements.

With this setup, forces were induced by the researcher following the defined axis. The response on the FTS was recorded and depicted in Figure 65.
From Figure 64 and Figure 65 we observe:

- Pressing the surgical tool forward in the direction of coupling (depth) results in a negative force being detected on the one of axis of the FTS. Herein referred as depth and depicted in blue colour.
- Pressing the surgical tool horizontally towards the robot results in a positive force detected on the FTS. Herein referred as horizontal and depicted in red colour.
- Pressing the surgical tool downwards results in a negative force detected on the FTS. Herein referred as vertical and depicted in green colour.
- There is an observable hysteresis which is normal with FTS in general.

Once the FTS and robot axis have been identified, the coupling procedure can be performed. To do so the robot end-effector was taken to a random start position and allowed to couple automatically. The system then corrects its position as already defined and attempts to couple with the tool.

The target was secured to a Force Torque Sensor with screws. Both tool and FTS were positioned by a stiff arm to replicate the expected conditions of the surgery room (Figure 64 and Figure 66).

![Figure 66- Scheme of the experimental setup for detecting forces applied on the patient.](image-url)
The robot will continually correct its position and orientation until the coupled status is achieved. If large corrections in orientation are necessary, the robot will not move itself towards the target, but correct the orientation first. It should also be noted that the mechanical tolerance of the pieces is 0.2mm.

### 2.6.3 LOAD APPLICATION ON THE ROBOT

Throughout this set of experiments a force was applied under three directions (Figure 67).

![Figure 67 - Force application on the end effector. The LBR3 holds the end-effector with attached tool while the researcher applies a force under the defined directions.](image)

The stiffness of the LBR 3 under these conditions was tested and estimate how much does the robot arm absorbed applied forces. Forces were not measured during this experiment. The interest of this experiment lays on the displacement the robot arm suffers.

### 2.6.4 STABILITY DURING DRILLING OF THE MAXILLA ON A PHANTOM PATIENT

Once coupling has been achieved, the next stage of the surgical workflow involves holding the target position while the surgeon continues his task. One of the tasks that need to be performed is the drilling of the maxilla for insertion of the fixation screws. To test this scenario the plastic phantom was used. The loose maxilla of the phantom was attached to the tool, and on the other side of the teeth the FTS (Figure 68 and Figure 69).
Figure 68 - Scheme of the experimental setup for drilling of the phantom’s maxilla.

Figure 69 - Experimental drilling setup. The LBR3 holds the phantom’s loose maxilla while the surgeon drills the phantom. The FTS is placed on the opposite side of the maxilla to measure the applied forces.
The target position was held by the robot and its displacement was measured as three holes were drilled in the maxilla; one hole from above and two laterals, from each side. The drill rotates at 20 000 rpm.

During this experiment the forces were measured with the FTS as well.

### 2.6.5 STABILITY DURING DRILLING AND FIXATION ON A SWINE SKULL

The robot arm has the task of holding the position as the surgeon drills and fixates screws on the maxilla bone. To mimic this scenario the surgical tool was fixed to the swine cadaver with screws. Given that the swine dentition does not resemble that of the humans, the tool was fixed with four screws on the side of the maxilla, as observed on Figure 71, left. The complete experimental setup can be observed on Figure 70.

Using a surgical drill at 40 000 rpm the bone was drilled three times along the bone near the surgical tool. Afterwards screws were inserted in these holes and tightened (Figure 72), simulating the fixation procedure during the maxillary repositioning. The used screws were not medical standard, but plain 3mm diameter steel screws. Contact between the end effector and the surgeon was noted throughout the experiment, in particular during the screw fixation, which presented some problems and did not grip easily. The surgeon rested his hand on the robot arm while pressing down and rotated the screw.

These two procedures were recorded and the robot position measured.
Figure 71 - Left: Detail of the surgical tool fixation to the swine skull. Right: Complete setup with swine skull, surgical tool, end effector and robot arm.

Figure 72 - Left: Drilling of the swine bone. Right: Screw insertion on the bone.