CHAPTER 4

DISCUSSION

Dentofacial deformities afflict a considerable percentage of the world’s population, for which many seek treatment. In numbers, approximately 20% of the world's population suffers from some major maxillofacial deformity and ultimately 5% of these cases can be considered to have a physical disability (135) (62). While orthodontics can correct dental occlusion to a certain extent, corrective orthognathic surgery may be necessary to correct misalignment of the jaws.

In surgeries involving the repositioning of the maxilla, the correct position of the upper jaw in relation to the base of the skull needs to be found. An accurate repositioning is extremely important not only for aesthetical reasons but as well in correcting malocclusions, which improves the ability to chew, swallow and breathe.

The current surgical approach consists of utilizing a plastic splint which defines the correct occlusal situation and allows placement of the maxilla in the desired final position in relation to the untouched mandible.

However this is only true for 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 a normal situation as much as possible. 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).

When the maxilla is thought to be in the desired position, it can be stabilized with a few plates and screws. During this period the maxillomandibular complex is still held manually by the assistant surgeon in the desired target position.

While the last years were distinguished by the creation and standardization of surgical methods, in present days the focus lies on precise treatment planning and the consideration of functional aspects of the whole stomatognathic system (140). Technical advances, such as rigid fixation techniques, bone graft harvesting techniques or bone substitutes, have further enhanced surgical success. However, despite these significant developments there is still room for improvement. Enhancement of visualization with 3D 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), computer-aided treatment planning and simulation tools which allow surgeries of complex cases with accurate predictions of surgery outcome and of soft tissue changes (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. It is key for the surgeons to note here, the limitations of the existing technologies in order to discern the advantages or the disadvantages for the presented surgical case.

4.1 DISCUSSION ON TECHNICAL SOLUTIONS IN CMF

Corrective surgeries in the cranio-maxillofacial (CMF) area have high accuracy requirements, which in turn have lead to the development of technically challenging solutions. The question here raised is: Once the surgical plan is on the computer, how can we transfer it to the OP for the higher benefit of the patient?

Importance should be laid on minimisation of the overall clinical error achieved with any technique, conventional, image guided or robotic (40). This error between the planned surgical outcome and the actual achieved result compromises of several errors along the surgical procedure including image acquisition, target selection, registration, tracking, etc (131). In literature it is quickly recognized that several authors discuss the registration process as the main contributor of inaccuracies (33) (78), as well being a time consuming step. A full automation is a key step to advance medical technologies. This would in turn result in widespread use of technologically advanced methods in surgery (48).

Using dental splints:

Nowadays the standard technique for orthognathic surgery is the employment of the plastic template or splint. This method has no assistance of computational methods and therefore the main source of error comes from the mechanical instrument and human eye. As already explained, the splint defines the correct occlusal situation only in a horizontal plane, leaving the vertical displacement highly dependent on the surgeon’s experience. There is room for improvement in this area which will lead to new techniques aiming to deliver an accurate implementation of the operation plan (27).

These dental splints are accepted, valid and proven methods in contemporary surgery, and also present comparatively low cost to other solutions.

Using image guided navigation systems:

The claimed accuracy of these systems is sufficient for tumour / foreign body removal and location procedures. They are normally used for these purposes but can also be used for more complex situations such as bone repositioning (117). Like other modern techniques, the estimated accuracy these systems can achieve depends mostly on the matching of the planning data with the intraoperative situation (Registration) and on the tracking of the patient / tool. However to perform the planned surgery the surgeon must compare the actual patient with the information presented on the screen, making the overall error highly human-dependent. Of particular interest for the hypothesis presented in this thesis is the work of Chapuis (27) (28). Chapuis’s work 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. Intraoperatively the patient is either placed in a Mayfield clamp, or tracked with a specific cranial tripod, necessary to maintain registration. The surgical procedure follows conventionally by using the fabricated splints, as well as with the aid of the navigation tool that shows if the occlusion and repositioning is being performed as expected. This approach combines the advantages of 3D visualization and tracking technology with cast based techniques for dental occlusion evaluation, and the obtained results indicated a precision within 1mm and one degree.

These results are difficult, if not impossible to achieve without computer assistance for complex movements. Nonetheless, as Cutting described in 1998 even if his device for bone fragment positioning could perform to accuracies of 0.1 mm, the applied accuracy in the hands of a surgeon was estimated to be two to four mm at best (39). Here it is safe to say that the problem lies literally in the hands of the surgeons, which are unable to achieve the accuracy and stability of a robotic arm (117).

Using Augmented Reality:

The AR approach in surgery aims to provide a more user friendly interface to enhance the already existing navigation systems. Instead of viewing surgical data on a computer screen representing the image space, the information is presented directly over the patient in the real world / surgical space (49). However it is technically more challenging to employ than stand-alone navigation systems. The requirement of exact matching between the real images in the visual field and the computer model, the 3D image processing and consequent stereo visualization make up the most demanding modules.

Like a normal navigation system, AR depends highly on the registration and tracking system technology; therefore, in case of optical tracking, rigid bodies are required to be fixed to the patient and in the case of projector based AR systems, the surgeon as well (128) (90).

Accuracy studies so far indicate a lower accuracy in matching the 3D model with the patient, when compared with other techniques, as well as a disadvantage in maintaining the correlation with the surgeon’s hands and visual field (154).

Using robots:

Given robot’s abilities in accuracy, stability and repeatability, many efforts have been made to advance medical robotics. Some successful systems have already been attained and are currently used on a regular basis. However, the modification of industrial robotics to surgery is not simple. Each patient changes considerably more than pieces in a manufacturing line, and often issues are raised such as safety and sterility. For this reason, the use of robotic systems in surgery will most likely develop towards coverage of specific procedure steps, which are possible to be addressed in a systematic way and which can benefit the most from the high levels of accuracy yielded by robots (54) (55).

Most surgical robots are large, and leave a massive footprint in the already crowded operation room. Only light-weight and handheld robots are the exception to this rule. Several research examples exploit this option since miniature robots do not consume too much space in the operating room and yet enables precise targeting and guidance. However more studies on their usability in surgery are required.

In particular to CMF the usage of robots is still on-going research, but it is widely agreed that there is a high potential for expansion of robotics in the field (117) (189) (66) (110) (139).

Regardless of the technical tool, the surgeon intends to carry out the surgery according to the previously gathered image data supported by his / hers own experience. The best tool to transfer the surgical plan to the operation room lies within the surgeon himself and his skills with the surgical devices. The surgeon therefore needs to choose the tool that better suits the situation and expected results. For that reason, it is necessary to be up to date with the current technology and have knowledge of the available tools. Ostertag in 1999 (129), considered that there was an unreflected enthusiasm towards high tech solutions in neurosurgery, with little advantages in accuracy and patient outcome. However, technology has since then developed and improved, and not only in neurosurgery but in every other surgical field, image-guided surgery and robotics have proven to be more accurate and reliable than their conventional counterparts (136) (165) (45) (126) (14) (84) (197) (86) (51).

It is sometimes difficult to convince people who do not work with technologically advanced systems about the benefit of these methods. Experience needs to be gained with any tool, whether navigation systems, robots or otherwise, and only then can a decision be made on what and when to use.

Discussions such as this thesis are thus needed to clarify the usage of so many technical alternatives and the best will be naturally (commercially) selected. Fundamental criteria for these decisions are clinical outcome, simplicity, time-consumption in surgery and / or preoperatively, accuracy, safety, cost effectiveness, and just as determinant, patient and surgeon comfort. Routine surgical interventions using navigation systems are nowadays common, and all indicate that the same will increase with other techniques and technologies.

4.1.1 ROBOTIC ASSISTED ORTHOGNATHIC SURGERY

To assist the surgeon in achieving an even higher accuracy that what is today’s standard, a robotic approach to orthognathic surgery has been developed (22). This proposed RAS approach intercepts the conventional surgical workflow in three steps;

- Registration with the patient before the maxilla is osteotomized;
- Present a stable, accurate target position of the maxilla;
- And removal of the surgical tool after fixation of the maxilla.

Plus an additional step to record the transformation to be performed during planning of the surgery (Chapter 1 - Introduction, Table 1).

This approach has the advantage of maintaining the conventional workflow almost unmodified. The surgeon is supported intraoperatively by the robot in positioning the maxilla in the planned target position. Additionally as an intelligent restraint system, it aids the surgeon in the correct repositioning by replacing the human dependent error sources during drilling and fixation of the bone segment.

Yet the success of such a robotic approach is dependent on one medical and technical challenge which required further work. Recognized with this new workflow is the necessity of applying a surgical tool only in some steps of the surgical procedure, removing the robot arm and / or tool from the surgical point of intervention, and bringing it into play when necessary. As a result, a tool will often be attached and detached from a single instrument holder during surgery. However, difficulties lay in accomplishing a coupling situation in a simple, intuitive way that minimises hazards to the patient, while maintaining the sterile conditions required in an OR.

Burgner described a solution for this problem where both robot and patient-bound tool are tracked externally with passive optical markers (23) (24). The navigation system monitors the markers on both tool and robot, determines a coupling axis, and then guides the robot arm automatically towards the tool. The claimed 1mm accuracy depends on several components of the system, being the larger error source the external optical tracking system using multiple markers and a large depth for small translations (186). Due to this tracking inaccuracy, adaptations on the system had to be made. And finally at the end phase of coupling the robot moves exclusively in an automatic mode and the applied forces on the end effector are measured. The sensed contact forces detected during the end phase help to guide the robot arm automatically to the final coupled position. If the forces overshoot a certain threshold a collision is recognized and the system comes to a halt.

Effectively, the contact forces which are required to guide the coupling system are also applied to the patient, increasing therefore the hazard of patient trauma especially when the maxilla is mobile.

For these reasons the hypothesis is raised to find a medically safe interface or coupling mechanism that permits fixation with the maxilla for accurate transfer the pre-surgical plan to the OR with minimum impact on the surgical workflow and improving the risk levels to previous designs.

The survey over existing coupling devices, referenced in Chapter 2.3- Medical robot coupling, showed that solutions for coupling robot arms and tools were found to be common in industry (180) (133) (193) (68). Industrial solutions for tool changers however depend highly on a constricted, closed and predictable environment where the exact position of the tools is known. In such circumstances the robotic system is able to guide the robot arm blindly and couple with the tool. 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.

However the survey revealed also that the existent solutions are not able to provide the sterility or safety expected from a medical robot (68). Patient safety is questioned when forces are applied to the tool in an uncontrolled, unexpected way (23). Ultimately what are non-existent are intuitive solutions; solutions in which the surgeon can rely on to help his/hers task without being bothered with line-of-sight, complicated mechanisms and complicated procedural steps.

4.2 DISCUSSION OF THE RESULTS

Although this study was conducted in the field of orthognathic surgery, other surgical interventions within CMF surgery such as Le Fort III osteotomy, fronto-orbital advancement, and cranial vault reshaping can profit from the application of this method.

Patient interface:

The presented surgical tool was designed to connect to the patient’s teeth, which was successful in accomplishing with similar ease as conventional dental splints. Nonetheless the lower part of the surgical tool can be modified to other anatomical structures. Possible modifications of the surgical tool have not been presented during this study, but it is predicted that the lower part of the surgical tool would be modified with the possibility to fix a plastic template with bone matching anatomy made from CT models. The tool would then be fixed to the bone with screws instead of wires, similar to the fixation process described by Marmulla (117).

In the case of the presented mouth-piece, the fixation is done with wires between the brackets and the indentations on the tool. The dental imprint provides the exact matching with the patient anatomy. If the dental adhesive is not strong enough to support the stress of holding the surgical tool and the brackets become loose, additional screws can be inserted in the maxilla as anchors for the support wires. Nevertheless this is unlikely to happen given the strength of nowadays adhesives (79) (176).

Image processing:

The coupling concept is dependent on the tracking accuracy permitted with a single camera and a 2D marker. This constituted the main image processing challenge which was successfully solved. In order to determine the tracking accuracy of this coupling method laboratory experiments were 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, the control system is able to restrict possible robot movements, such that the robot moves only within a safety corridor defined around the planned path profile.

The concept for depth calculation, using a quadratic curve to map the 3D space was successful in discerning the correct distance with a reasonable amount of error. Within the tracking volume of the device the depth error was found to be between 0.1mm and over 3.5mm as the camera tilted away from the normal axis of the target. Within the tracking volume the calculated median depth error is 1.53mm, with an interquartile range of 1.93mm. The overall coplanar angle error was found to be between 0.1º and 1º following the same behaviour as depth; lowest when close to the normal vector of the target plane, higher when tilting. The median coplanar angle is 0.33º with interquartile range of 0.411º. Only the measuring error of the XY plane was found to be almost constant in the tracking volume, being lower when the camera is closer to the target. The median error is $30.34e^{-4}$mm with an interquartile range of $8.3e^{-5}$ mm.

From this statistical data is concluded that the bigger the circles are perceived in the image plane, the lesser the error. That includes the skewed circles (ellipses) in disadvantageous positions, which lower the area, and amount of data points on the edge of the detected ellipse. The lowest errors within the tracking volume are found in the normal vector and passing through the centre point of the target plane. With this information known it is possible to determine the best possible procedural workflow that would minimise these errors. The conducted analysis came to support the assumption that the best approach path is the one that initially corrects the orientation of the camera without moving forward towards the target. Once the end effector is close to the perpendicular axis the robot will move forward. The X/Y position and the co-planar orientation are also corrected before the robot is moved forward in depth.

What was later observed in the laboratory experiments is that with this method the robot frequently stops moving forward to adjust his orientation. This behaviour is due to measurement fluctuations within the image processing. The stability of the measurements is highly dependent on the segmentation of the image frames. Small pixel variations on the edges of circles can shift the fitted ellipse just slightly and with it the calculation of the target coupling axis. These variations were filtered and averaged through time to improve the accuracy of the position estimation. This approach proved to be acceptable and coupling without collision was possible. Nonetheless the inclusion of more tracking circles, possibly concentric, as suggested by Estaña (56), can improve the stability of the measurements. This would in turn lead to a more fluid movement of the robot arm.

Since the camera is placed on the coupling axis, the line-of-sight problem, inherent from external optical tracking systems, does not apply. The line-of-sight in this case is constantly open by definition, allowing continuous updated target information to be available throughout the robotic approach and coupling procedure. The continuous real-time image processing allows corrections in robotic movement and guidance, which is particularly useful since the target is not fixed in space.

Sterility and workflow:

The key to the sterility of the system is provided by the in-between piece with orientation edges and fixation rings. A sterile drape is attached to the middle of this piece which will be pulled over the robot arm with the help of a second assistant. It is noted that a plastic overlay of the same shape as the robot arm, reinforced at the robot's joints would be a better solution to maintain sterility, instead of the sterile drape.

Both the surgical tool and in-between piece are sterilizable by conventional steam procedure.

Prior to surgery the robot is prepared and set up for operation. The end effector is already fixed to the extremity of the robot arm, and the OR assistant will bring a sterilized in-between piece with the sterile drape to the robot, attaching one of the ends to the camera housing and securing by rotating the fixation ring. The sterile drape is then pulled over the robot covering it completely and isolating it from the OR. This way the robot is completely separated from the sterile area.

With the proposed solution the fixation rings have proven to be of annoyance to the assistants. This is due to its lengthy thread which made the procedure take longer than necessary (chapter 2, section 2.4.4.2 - Preparation for surgery). Improvements on this piece can be made with the usage of a larger thread size. The size of the thread is constrained not only by the overall size of the prototype, but as well by mechanical thread standards. Alternative solutions such as mechanical clamp or electromagnetic can also be used to achieve similar structural stability with shorten connection time.

The device can be miniaturized with another choice of lenses and camera. It was learned that a higher zoom lens, would also suffice if it would be able to focus nearby. The zoom lens would have a smaller capture area and would therefore force the circular markers to be smaller. This in turn would allow the surgical tool to be smaller and lighter as well. Placing the camera and lens further away would produce a longer end effector, but would still be able to implement the concept successfully. However the robot arm flange still needs to be as close as possible to the surgical tool in order to avoid that a small orientation error would produce a great impact on the general accuracy of the target position. For this reason the end effector was optimized as presented.

Intuitive usage:

The force control mode already existent in several robotic applications provided the intuitive feeling of guidance, as the surgeon steers the robot to the correct location. The surgeon can guide the robot by hand until completion of the coupling procedure, which is an advantage regarding previous methods (23).

Additionally, the integrated camera is less expensive than a navigation system, answering therefore to the cost saving intentions of surgical practices (139) (196).

Zero force coupling:

The hypothesis raised in this thesis is the ability to couple the robot arm with the patient-bound tool without collision. To assert this hypothesis the LBR3 was used and tested under laboratory conditions with a phantom patient, as well as with a swine skull.

Since the LBR3 is a light weight robot, certain conditions apply. Hence some of these conclusions are specific for this robot, in particular the ones referring to the stability of the robot.

As it was observed throughout the experiments, it is possible to bring the robot into the coupling mechanism without collision. As the coupling procedure concludes the pieces brush together; the mechanical tolerance of the pieces is 0.02mm, a value which is higher than the minimum step of both used robots, as well as lower than the expected depth error.

During the experimental setup it was observed that the robot successfully enters the coupling area without exerting forces on the tool. However as it proceeds further corrections in orientation and depth have lead to the pieces brushing with each other, thus creating forces up to 0.4N, or 39.2g. This value is insignificant compared with weight of the tool (120g) or the forces applied subsequently coming from securing the fixation rings (higher than 2N or 200g). These forces are naturally not applied by the robot but by the surgeon when securing the design. The LBR3 is not a stiff robot, but it is able to compensate for forces applied externally, and in little more than one second recover the original position, confirmed by the experimental results. However the LBR3 is unable to maintain a stable target position if the applied load is dynamic.

Robot arm choice:

The prototype was mounted on a modified Stäubli RX90 robot (Caspar system by Orto-Maquet (Rastatt, Germany)) as well as a light-weight robot, the LBR3 from KUKA Roboter Gmbh (Augsburg, Germany). Initially the Stäubli RX90 was selected as a follow up of the previous development on robotic assisted orthognathic surgery, and as the study progressed a growing interest was taken on the usage of a smaller robot to conduct the same procedure.

Although both robots have successfully been used with the described concept, the LBR3 has an advantage. The RX90 requires an extra FTS to program the force-control mode, 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 (Chapter 2, Figure 37).

Consistent with Minimally Invasive Surgeries, the trend nowadays is to reduce not only the size of the surgical opening (with all the benefits it incurs (67) (185)) but the size of the operating devices as well (9). For this reason light-weight and miniature robots are being researched and adapted to surgery (160) (158) (11). The LBR3 has increased flexibility and overall sensory equipment dedicated to the sensitive area of human interaction. This robot then brings to the robotic assisted orthognathic surgery a worthy benefit that triggered the interest of the research. The question of whether this type of robot is suitable for surgical use is answered with the conducted experiments.

Light-weight robot stability:

Depending on the amount of force which it is applied on the robot arm, the target position can shift almost 1.5mm. Upon release of the applied force, the robot arm overshoots the target position, often more than the original displacement. This overshoot can be compensated by releasing the force progressively.

Although the target position is recovered with a minimal error in position (below 0.01mm), the orientation of the robot fledge presented a more significative error. The orientation error in axis A and C (horizontal and vertical axis respectively), could grow up to almost 0.06º, in the worst case observed.

As it is known, a small rotational error can produce a large error at the end of a lengthy tool. In the case of this prototype, with a 12cm long tool a resulting 0.1mm maximum error is expected at the end of the tool.

This amount of error is medically acceptable for the surgery in question. The direction of this displacement error is vertical to the maxilla, which could tolerate an error up to one millimetre without the necessity of further bone removal or down-grafting. Possible solutions to lower this value would be to make the surgical tool shorter, and / or to take advantage of the most stable angular axis (B or depth) which has a lower repositioning error. Under that angle the worst observed error was of 0.007º which would produce an error ten times lower. To accomplish that, the end effector can be rotated and fixed to the robot arm from the top of the housing. This change in axis would mean that the highest error direction would be transferred to the XY plane, or horizontal plane of the maxilla. In this situation this error is transferred to an even more critical area. Reason being that the symmetry with the mid-face line would be compromised, and with it the expected result of better aesthetic outcome (31).

Also noted with the LBR3 is the stability difference in its axis. The most sensitive axis to external forces is the same axis as the depth, or the coupling axis. In opposition the vertical axis is the most resistant. This is because the most common load applied on the robot is done vertically.

Light-weight robot behaviour during drilling and fixation of the maxilla:

Once the robot is coupled with the tool, the next stage of the surgical workflow involves holding the target position while the surgeon continues his work. Two of the tasks that need to be performed are the drilling of the maxilla and the fixation with screws and mini-plates.

To mimic this scenario the surgical tool was fixed to the phantom patient, but since the plastic skull is softer than bone, further testing with a swine skull bone was performed. This helped to better understand the behaviour of this light weight robot under more realistic conditions. The robot arm has the task of holding the position as the surgeon drills and fixates screws on the maxilla bone.

The high speed of the drill does not create a visible vibration on the robot position. But when pressing the bone to pierce it with the drill tip the result is equivalent to the application of a constant load in the drill direction. The opposite happens when rotating the screws. The applied force is in the direction of the screw and dynamic with every twist and release of the screwdriver.

While drilling and fixating screws on the swine cadaver, the surgeon rested his hand on the robot and pressed down so that the screw would better grip the bone. This behaviour was not predicted with the design. The reason the surgeon supported him/herself on the robot was due to the proximity of the coupling device to the surgical area and simple discomfort. This observed behaviour produced a mixture of constant and dynamic loads being applied to the robot and natural displacements of the target position (over 0.3mm). These displacements do not pose a considerable hazard to the patient, since the soft tissues are flexible enough, and the robot was able to recover the original position afterwards.

The LBR3 has shown its ability to handle this procedure and the loose maxilla can be held in position while the surgeon performs his tasks. Although the robot displaced the target position under the application of external forces, the recovery of the original position is achieved within the desired error limits.

4.3 CONCLUSION

The OR is an environment populated with human actors. The introduction of a robot to assist the surgeon undoubtedly requires an intuitive control over its function. Even though several progress indicators in RAS were already described in the literature, there is little analysis of a robot’s practical use under clinical conditions. In particular little discussion is presented in the interaction between the agents of the system (patient / surgeon / robot) and the influence of external conditions upon the robotic system, and ultimately in the surgery outcome. The research presented in this thesis set out to develop a prototype for safe interaction between these agents. Industrial robots can be adapted with a FTS at its flange to convey this intuitive feeling, but it is in smaller light-weight robots with integrated sensors on each joint which will be the future in intuitive interaction.

The interaction between robot and operator is also reflected in the usage of surgical tools. So far most robotic systems use a single tool, but some robots like the telemanipulator DaVinci use several surgical tools during one procedure, and the tendency in the future of robotic assisted surgery is to use more tools and more frequently. The interaction between the robotic tool, surgeon and patient raises a few safety concerns. For this reason among other research efforts are solutions and methods for coupling and decoupling surgical tools from robotic arms.

In this study, the use of a camera embedded in the end effector achieved a better coupling solution. The coupling problem was reduced to a robot-arm / moving-target relative positioning problem. The relative position is acquired by extracting information from the circular markers on the tool. And the robot position is calculated to move relative to the target.

Due to the nature of the surgery room this coupling method was further enhanced with a specific mechanical solution to maintain sterility, while at the same being intuitive, safe and force free.

Technically the key features of the designed mechanical prototype and image processing are:

- The ability to completely separate the sterile area from the non-sterile by means of the in-between piece.
- Surgical tool with a possibility of fixation to the patient’s dentition and possibility to be applied in the future to other rigid anatomical structures.

- Surgical tool which can be tracked by the robot arm, and provides an exact interface matching between the robot and the tool, eliminating therefore the human error.
- Single camera tracking mechanism that allows the accurate guidance of the robot arm to the surgical tool.
- Image processing for a single-camera with 3D and 6DOF target-position information extraction.
- Force control mode for intuitive guidance.
- Force free coupling of robot arm with patient-bound tool.

Tests with the light-weight robot LBR-3 contributed the information for realistic surgical conditions, drilling and screw fixation, with both plastic phantom and swine cadaver, supporting the previous developments in robotic assisted orthognathic surgery (22). Finally this study concludes that the LBR3 is adequate to handle this procedure. The loose maxilla can be held in position while the surgeon performs his tasks, and a force free intuitive coupling for medical robots is possible, pointing towards a method to be included in the development of new medical robots to achieve a safe, sterile, reliable and predictable design.

4.3.1 FUTURE WORK

The research results discussed in this thesis have shown the viability of the method, yet further tests to assert it’s usability with actual patients have not yet been completed.

The prototype presented in this study can be further developed and improved. One major point is that the device can be miniaturized with another choice of lenses and camera. It was learned that a higher zoom lens, would suffice if a close enough focal point could be achieved. The usage of a zoom lens would force the circular markers to be smaller, which in turn would allow the coupling interface to be smaller and lighter as well. As well the inclusion of more tracking circles, with possibly concentric markers, we can further improve the stability of the measurements. This would in turn lead to more fluid movement of the robot arm. Finally the threads of the locking rings can also be improved with a non-standard thread, or a new locking mechanism. Finally, this prototype could be adapted and tested with surgeries other than orthognathic.

It is hoped that this study will lead the way forward to future force free applications in robotic assisted surgery, increasing the intuitive usage of robots in surgery while maintaining the required safety and sterile conditions.