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Methods for end-effector coupling in robot assisted interventions

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Abstract— **Robot assisted interventions often require coupling and decoupling of the robot to/from a specific tool. By using manual gripper changing systems these operations are facilitated, but the robot has to approach to and move away from the coupling position. Industrial applications are mostly based on movements which are teached-in, since the working environment is perfectly described (i.e. working cell). Especially in robot assisted surgery we are facing non fixed tools to which the robot has to be coupled (e.g. a holding device attached to a mobilised bone) and restricted working areas with special safety requirements. In this paper we present an automatic end-effector registration method and a semiautomatic coupling procedure exemplarily for robot assisted orthognathic surgery. By using means of an optical localisation system and force-/torque sensing, the coupling procedure is controlled by a multi-sensor data fusion approach. The developed methods can be adapted to any robot assisted intervention.**

I. INTRODUCTION

Distinctive oral and maxillofacial anomalies often have to be corrected by orthognathic surgical treatments(compare Fig. 1). Especially osteotomy of the maxilla in the Le-Fort-I plane is counted among the most frequently performed interventions. Conventionally the planning of these osteotomies is based on two dimensional X-ray photographs and clinical analysis of the teeth and temporomandibular joint position. Mechanical articulators enable the preoperative simulation of the surgery using cast models of the jaws which are mounted in their relative position to each other. Dental splints are fabricated and represent the initial and target situation of the mandible. Such a splint is made of plastic and represents the imprint of the bite. It is used intraoperatively to establish the preplanned correct relative position of the mobilized mandible, which is then fixated by the surgeon in the target position with osteosynthesis plates. Nowadays methods of computer-assisted surgery [1][2] find their ways more and more into the operation theater, thus also in maxillofacial surgery.

The preoperative planning phase in maxillofacial surgery can be supported by computer-aided cephalometric analysis. These methods are nowadays widely accepted, since they are still based on two dimensional patient data. In comparison 3D cephalometric analysis and dental occlusion analysis implemented within simulation environments requires computation of virtual patient models and therefore acquisition of CT or MRI image data [3][4]. Advanced planning approaches include the possibility to perform virtual mobilization of the mandibles and simulation of the target situation [5][6]. Some of these approaches also include the simulation of facial soft tissue deformation according to the repositioning of the underlying structures [7][8]. Nowadays rapid prototyping technologies enable fabrication of dental splints [9] based on three-dimensional simulation environments. These splints are supposed to provide more accuracy than conventionally fabricated ones. All these three dimensional planning and simulation methods are not used regularly, since they are mostly in experimental state and still not evaluated sufficiently.

To transfer the preoperative planned data into the operation theater, predefined landmarks, either anatomical or fiducial, are used for registration purposes, i.e. matching the 3D model and the patients site coordinate system. These landmarks are mostly located manually in CT/MRI datasets preoperatively and with tracked pointing devices intraoperatively [10]. Navigation of the mobilized mandible can afterwards be performed for example by tracking the dental splint [11] and by visualizing the location in CT or MRI data sets [3][12][13]. If preoperative defined cuts need to be performed, the instrument itself has to be navigated under continuous control in CT or MRI images.

Though intraoperative navigation [14][15] supports the surgeon positioning the mobilized mandible, the fixation procedure is still free-hand performed. Additionally navigated computer-assisted methods suffer from a limited accuracy [16] due to system limitations, tremor and registration errors. Virtual 3D models are reconstructed from CT data of the

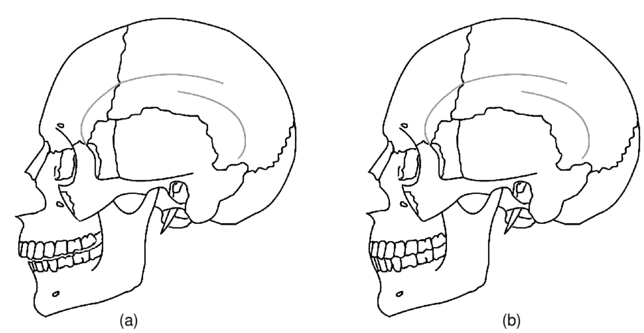

Fig. 1. (a) Lateral schemtic view of dentofacial abberrance - the dental occlusion is malfunctioning. By repositioning the maxillary skeletal osteotomized segment in the Le-Fort-I plane a surgical intervention leads to normal aesthetic and functional anatomy. (b) Lateral view of correct dental occlusion.

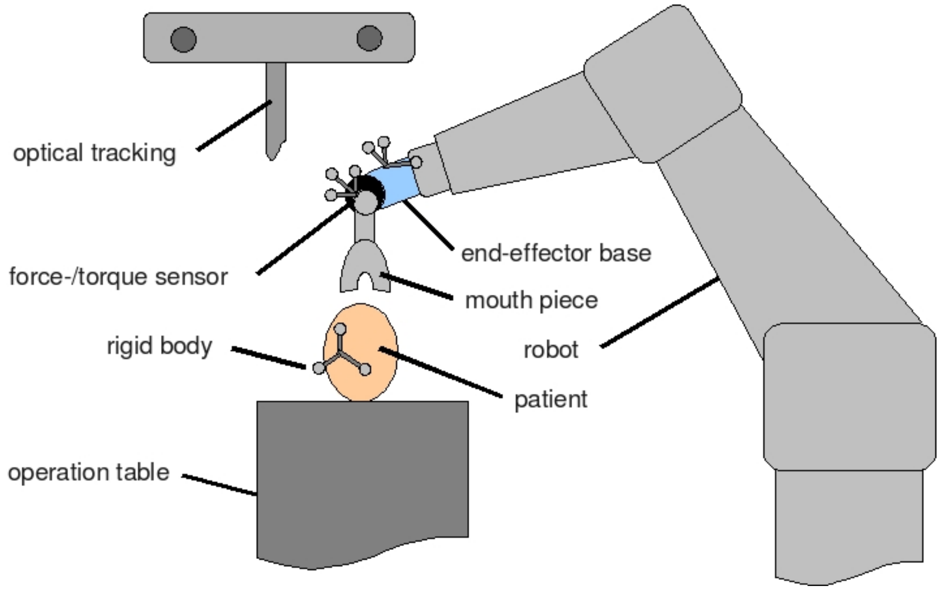

Fig. 2. Schematic overview of the system: The robot is equipped with the developed end-effector base and the mouth piece. An optical tracking system is localizing the position of three rigid bodies: one attached to the bone of the patient and two attached to the end-effector parts. A force-/torque sensor is attached to the end-effector base.

patient. This is an image data acquisition method which involves high radiation dose rates for the patient and which is conventionally mostly not necessary for ordinary maxillofacial interventions.

To overcome the mentioned disadvantages we are developing a robot system for maxillofacial surgery. A schematic overview of the system is given in Fig. 2. Unlike the presented approaches above, our system does not include three dimensional planning and simulation of the intervention based on CT data, if it is not foreseen in the conventional workflow. In fact the planning procedure can be performed conventionally using the mechanical articulator to capture the initial situation and target situation of the mandible with the robot.

Intraoperatively the robot is used as an intelligent assistant performing the relative replacement of the mobilized mandible and holding the according bone segment in its preplanned target position while the surgeon is fixating it. By means of a localization system patient movements are compensated by the robot. The working area of the robot (the mouth of the patient) is small-sized and contains critical structures (e.g. trigeminal nerve). To avoid exerting forces to the patient while moving the bone segment in the target position and during the fixation procedure, the robots end-effector needs to be equipped with a force-/torque sensor. We developed a prototype end-effector for robot-assisted Le-Fort-I osteotomies [17], which consists of two parts (see Fig. 3), which can be coupled using a manual gripper changing system (model MGW050, GRIP GmbH, Dortmund, Germany). To allow fast and secure coupling and decoupling of the mouth piece to the end-effector base, we developed a semiautomatic coupling procedure. Since varying maxillofacial interventions require differently designed mouth-pieces dependent on the bone segment to which it has to be attachable, we are also introducing an automatic end-effector registration approach in this paper.

II. MATERIALS AND METHODS

We are using a Staeubli RX90CR robot which performs movements in two modes: autonomous and hands-on. Both modes require the confirmation of the surgeon, who has to press a dead men's switch. In the hands-on mode, forces and torques exerted at the end-effector by the surgeon are used to calculate the desired direction of the motion.

To acquire the patients location an optical localization system (NDI Polaris System, Waterloo, Canada) is used intraoperatively (compare Fig. 2). Passive reflecting marker spheres (assembled to rigid bodies) are attached to the

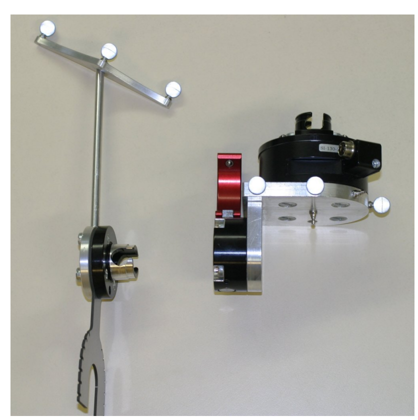

Fig. 3. The end-effector for Le-Fort-I osteotomies consists of two parts: The mouth-piece (left) can be coupled with the end-effector base (right) with a manual gripper changing system. The end-effector base is equipped with a force-/torque sensor and can be attached to the flange of the robot. Reflecting marker spheres are mounted to both end-effector parts, to facilitate tracking by an optical localisation system.

patients orbita and to the mouthpiece. Even though the end-effector base location is given by the forward kinematics solution of the robot, it is also equipped with a rigid body. In this case the tracking system provides redundant information, which is used to assure the correct positioning. The patient's head is seated in a vacuum cushion which can be fixed to the operation table by hook-and-loop fastener and therefore excessive movements of the head are avoided. Since small movements cannot be excluded, they need to be registered by the localization system and compensated by the robot.

Different maxillofacial interventions require variable mouth-piece designs, depending on the way of attaching the mobilized bone segment. By the manual gripper changing system at the end-effector base, different mouth-pieces can easily be attached and detached. The first step towards a semiautomatic coupling procedure is to assign the rigid transformation between the two coupled end-effector parts, i.e. the transformation between the mouth-piece and the base. Additionally the transformation between the coordinate system of the robots tool center point (TCP) at the flange and the end-effector base needs to be determined. The following registration procedure was developed to automate the calculation of these transformations.

A. Automatic end-effector registration

Motivated by the method introduced by Knoop et al. [18], the automatic registration of the end-effector in coordinates of the robot is based on elementary geometrical relations. The main idea is to move the attached end-effector along the x-,y- and z-axis and in the xy-/yz- and xz-planes of the flange coordinate system and capture the locations by the optical tracking system.

Since both end-effector parts are tracked during the automatic registration procedure, all necessary transformations can be determined, i.e.

- ${}^{TCP}_{EE}T$ - Homogeneous matrix representing the coordinate transformation between the robots TCP and the end-effector coordinate system.
- ${}^{EE}_{MP}T$ - Coordinate transformation matrix between the end-effector and the mouth-piece in the coupling position.

Respective locations representing the starting and the ending of the movement are characterized by simple rotational and translational relations. Since the movements between start and end point only happen in planes, two-dimensional geometrical equations can be used to calculate the required registration information. The defined rotation angles facilitate setting up the equations. Fig. 4 illustrates some episodes of the registration procedure.

To register the end-effector with the Staeubli RX90CR robot we chose seven configurations given in Table I to determine ${}^{TCP}_{EE}T$ by tracking the location C_n $(n = 0..6)$ with the optical tracking system. C_0 is the location in the standard configuration, acting as the starting point for moving to the six other configurations. Vector $\overrightarrow{C_1C_0}$ is corresponding to the z-axis of the flange coordinate system, $\overrightarrow{C_3C_2}$ corresponds to the x-axis. The y-axis follows from the cross product

Fig. 4. Episodes of the automatic end-effector registration procedure. (a)-(b) Movement along the y-axis of the robot. (c)-(d) Positions for rotating the end-effector in the xz-plane of the flange coordinate system. (e)-(f) Start and final location of the rotation in the xy-plane.

of $\overrightarrow{C_1C_0}$ with $\overrightarrow{C_3C_2}$. By capturing the end-effector position with the localization system in these three different robot configurations the corresponding vectors are determined and used to set up the 3x3 rotation matrix ${}^{TCP}_{EE}R$ of ${}^{TCP}_{EE}T$:

$$ {}^{TCP}_{EE}R = \begin{bmatrix} \overrightarrow{C_3C_2} & \overrightarrow{C_1C_0} \times \overrightarrow{C_3C_2} & \overrightarrow{C_1C_0} \end{bmatrix} $$

To calculate the translation ${}^{TCP}_{EE}t = (t_x, t_y, t_z)^t$ between the origin of the flange coordinate system and the end-effector coordinate system, the robot is brought first into the standard configuration (C_0). In this configuration the end-effector is rotated in the xy-, yz- and xz-plane to determine three vectors representing coordinates of the sought translation. In the first step axis six is rotated about 60° (C_4, compare Fig. 4(e)-(f)). The vector $(t_x, t_y, 0)^t$ in flange coordinates can be determined by using the known rotation of the coordi-

TABLE I

ROBOT CONFIGURATIONS USED FOR THE AUTOMATIC REGISTRATION

	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5	Axis 6
C_0	0°	−45°	135°	0°	0°	−90°
C_1	0°	−135°	225°	0°	0°	−90°
C_2	−20°	−45°	135°	90°	20°	−180°
C_3	0°	−45°	135°	90°	−20°	−180°
C_4	0°	−45°	135°	0°	0°	−30°
C_5	0°	−45°	135°	0°	−60°	−90°
C_6	0°	−45°	135°	90°	0°	0°

nate axis between the tracking coordinate system and the flange coordinate system and simple geometrical relations. Equivalent robot movements (C_5,C_6) lead to $(0, t_y, t_z)^t$ and $(t_x, 0, t_z)^t$. The required translation is then given by:

$$^{TCP}_{EE}t = \frac{1}{2}\left(\begin{bmatrix} t_x \\ t_y \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ t_y \\ t_z \end{bmatrix} + \begin{bmatrix} t_x \\ 0 \\ t_z \end{bmatrix}\right)$$

B. Semiautomatic coupling

During maxillofacial interventions it is necessary to remove the robot from the direct surgical manipulation area, e.g. for mobilizing the mandible. Afterwards the robot has to move back to the patient, be coupled to the mouth-piece and perform the preplanned repositioning. The implemented hands-on mode allows the surgeon to move the robot in a position where it does not disturb the surgical workflow. This mode provides in an intuitive way to manipulate the robot movement by simply exerting forces and torques in the desired direction. That's why we chose to develop a semi-automatic coupling method, where the surgeon is motivating the movement towards the mouth-piece.

The coupling procedure is divided in three phases (see Fig. 5). At the beginning the robot is brought force-controlled by the surgeon to a position next to the mouth piece. The following semiautomatic approach phase is also force-controlled, but the movement is restricted to a preset axis. Autonomous movement of the robot is performed in the last automatic coupling phase, where the gripper changing system part at the end-effector base slides into the mouth-piece part. To decouple both end-effector parts an automatic decoupling phase is available. The following sections will describe these phases more detailed.

1) Force-controlled free motion phase: This phase represents the beginning of the coupling. The robot is located somewhere in the workspace and has to be moved controlled in direction of the mouth-piece. During this phase the robot can be moved force-controlled by the surgeon. Exerted forces and torques at the end-effector base are projected to the robot coordinate system and used to calculate the next required position. The speed of motion is limited to 5% of the maximum robot motion speed and is proportional to the quantity of the force.

Free movement of the robot is allowed since the safety region in form of a cone (apex angle 60°, height 200mm) around the mouth-piece is not reached. This safety distance marks the beginning of the semi-automatic approach phase.

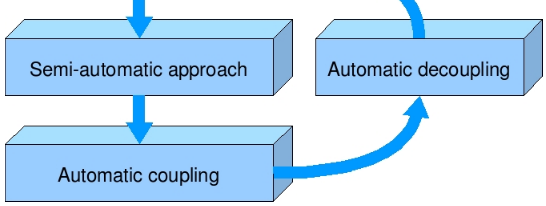

Fig. 5. Workflow of the phases during the coupling procedure.

Fig. 6. By applying forces and torques to the end-effector base (right), the coupling motion towards the mouth piece (left) is induced by the user.

2) Semi-automatic approach phase: In this phase the operating space is restricted to the coupling axis. This axis is calculated in real-time by the main computer, which captures the actual locations of the end-effector base and the mouth-piece. Corresponding to the coaxial-axis of the manual gripper changing the coupling axis is referred as "coupling path" in the following. Forces exerted to the end-effector base are projected to the coupling path and are serving to control the movement and the speed of motion. Fig. 6 illustrates the semi-automatic approach phase: The robot moves along the coupling axis towards the mouth-piece.

The work-space restriction to the coupling path causes at first, that the robot moves towards the coupling axis and the approach along the axis in direction of the mouth-piece subsequently. To facilitate user interaction exerted torques are ignored during this phase. The rotation of the end-effector is generated automatically.

The approach phase ends when the distance between the final coupling position and the end-effector base is less than 28mm. This value derives from the length of the male manual gripper changing system part (i.e. 22mm) adding the desired value for the safety distance.

3) Automatic coupling phase: After finishing the approach phase and therefore the achievement of the coupling position, only a translational movement in direction of the target position (connection position) is remaining. During this last coupling phase forces and torques are not allowed to be exerted to the patient, since it may have negative impact to appending soft tissue and critical structures in the proximity area of the mobilized bone segment. On this account the robot is moving autonomously along the coupling axis to enable monitoring of forces and torques at the end-effector base in this phase.

The movement is performed successively with 0.1mm (ΔL) steps in direction of the connection position. Rotational corrections are performed with 0.1° per step. The allowed force exerted to the end-effector base is restricted by a

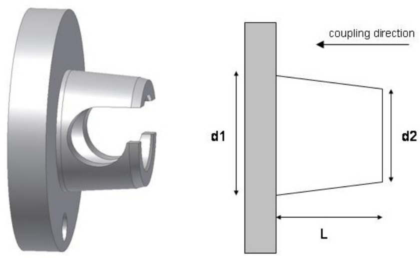

Fig. 7. Profile of the male coupling part from the manual gripper changing system (left: CAD drawing, right: scheme of the profile). In comparison the modified profile is now cone-shaped, i.e. d2 < d1.

threshold (empirically set to 5N). Exceeding this threshold results in an immediate stop of any movement of the robot. The robot has to be brought in safety clearance by the surgeon before the coupling procedure can be repeated.

Since the localisation system does not provide sufficient accuracy to couple the end-effector parts without getting stuck, we modified the profile of the manual gripper changing system, which connects both parts free of play and with positive locking. The male part is now cone-shaped and allows sliding into the other part easily, but still ensuring a well-defined coupling position. Fig. 7 shows the modified profile (compare Fig. 3).

To reduce measuring noise of the localization system the actual position of a rigid body is approximated by using a moving average filter over the last measured values. Due to the not completely sufficient accuracy of the optically tracked locations of the end-effector and the mouth-piece, we additionally implemented a force-controlled adjustment procedure. Forces that occur during the coupling procedure at the end-effector base are measured in all three dimensions. If the detected entire force does not exceed the threshold, information about the direction in which the movement has to be corrected in the next step can be derived. It is obvious that the force appears in the opposite direction of the correction movement which needs to be performed to prevent a deadlock of the two parts.

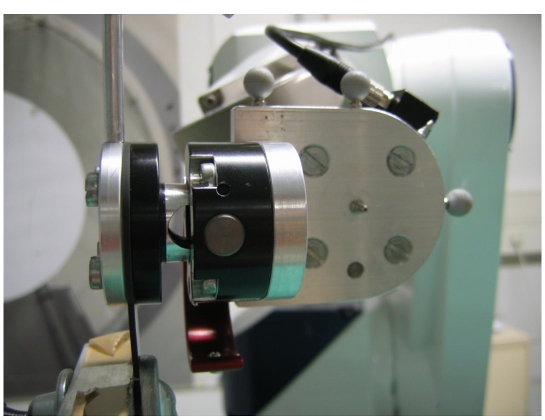

Fig. 8. Automatic coupling phase: The end-effector base is sliding into the manual gripper changing part at the mouth-piece.

The automatic movement of the robot is initiated by the surgeon, who is visually controlling this phase. The movement is confirmed while the dead man's switch is pressed. The robot stops immediately when the switch is released. Additionally the graphical user interface of the system supports the surgeon by providing a three-dimensional simulation of the phase and displaying current values (e.g. measured force, remaining distance to the connection position). Fig. 8 shows the end-effector base and the mouth-piece in the last phase. After completing the coupling phase, the surgeon has to operate the hand lever at the manual gripper changing to fix the coupling position.

4) Automatic decoupling phase: Decoupling the end-effector parts corresponds to the reversion of the coupling motion. At first the surgeon has to release the hand lever of the manual gripper changing system to open the coupling. Afterwards the robot moves along the inversed coupling axis with 0.1mm stepwise. If the distance between the coupling position and the end-effector base exceeds 25mm, the speed of motion is increased till a safety distance of 100mm from the mouth-piece is reached. Afterwards the robot can be moved without workspace restrictions in the hands-on mode.

III. RESULTS

Since the semiautomatic coupling is dependent on an accurate registration of the end-effector parts in the forefront, we are first addressing the accuracy of the stated registration method and afterwards presenting the results for the coupling procedure.

A. Accuracy of the end-effector registration

The mean error for the registration procedure was at first determined theoretically and afterwards proven in experiments. Following the assumption that measured coordinates of a rigid body are situated within a sphere around the real location with diameter Δe (in mm), i.e. the mean error of the localization system. The mean error of the registration can be described as probability density distribution and has $2.26\Delta e$ as expected value. In our case the NDI Polaris system with a stated mean error $\Delta e = 0.35mm$ and the Staeubli RX90CR robot with a stated repeat accuracy of $\pm$0.02mm, result in a theoretical mean error of 0.84mm.

We confirmed this value in experiments, where we measured the end-effector geometry with a FARO Platinum Arm (FARO Technologies Inc., Florida, USA) with an accuracy of +/-0.013mm with a cone point probe to determine the registration parameters. These were used as reference values for the results calculated by the automatic registration procedure. By varying the relative position of the localization system to the robot, we measured four groups each with three registrations. Conspicuously the deviations between the result (i.e. the homogeneous transformation matrix) in one group were very small with about 0.05mm. Between the groups we determined deviations about 0.3mm. The mean error of the calculated registrations in respect to the manually determined reference measurement for the 12 experiments was 0.81mm.

TABLE II

RESULTS OF THE SEMIAUTOMATIC COUPLING EXPERIMENTS.

F_{max}	2.8N
$\overline{F}$	0.4N
$\overline{Steps}$	284
MAD	0.36mm

B. Accuracy of the coupling

Accuracy of the coupling procedure was determined in an experiment by measuring reference points located at both parts of the manual gripper changing system. We accomplished 30 semiautomatic coupling sequences with varying starting positions of the robot in respect to the mouth-piece, which was fixed with a clamp to the operating table in altering locations and represented possible patient locations during surgery. We used the FARO Platinum Arm with a cone point probe to capture the reference positions. Table II illustrates the results of the experiments. From the 30 trials 2 coupling attempts were aborted due to the exceeding of the maximum allowed force of 5N. Restarting the procedure in these case led to successful couplings.

The maximum force measured during the experiments was 2.8N and therefore far below the maximum allowed force of 5N. Forces in this order of magnitude are not supposed to have negative impact on the patient. The force averaged 0.4N and the medial number of steps for the automatic coupling phase was 284. The mean absolute deviation (MAD) in the reference points amounted to 0.36mm.

IV. CONCLUSIONS AND FUTURE WORKS

The presented closed-form automatic registration method for varying mouth-pieces and the semi-automatic coupling procedure allows accuracies in sub-millimeter range. The developed methods are appropriate for intraoperative use, because allowed forces exerted to the patient are restricted and the interaction with the surgeon is perpetual. Measured forces during the automatic coupling phase did not pass 3N and are not supposed to have negative impact to appending soft-tissue and critical structures in the proximity area of the mobilized bone attached to the mouth-piece. Our future work will be focussed on the evaluation of the whole process chain for robot-assisted Le-Fort-I osteotomies. Since we already evaluated our system on phantom skulls, in a next step trials with animal and human preparations will be performed. Patient trials are already affirmed by the ethics commission and will take place in the near future. Additionally the empirically set threshold for the allowed maximum force exerted to the mandible will be approved.

Our developed coupling and decoupling methods are generic and suitable for use in cases when a robot has to (semi-)automatically couple to a defined tool under visual control. The coupling procedure can be performed completely automatic if there is no need for user motivated robot movement and no special safety conditions need to be satisfied respectively. In the scope of our 6th framework program IST project AccuRobAs (Project No. 045201) we will adopt the developed sensor fusion methods to improve the accuracy of light-weight robot arms.

V. ACKNOWLEDGMENTS

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