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Flat-Panel Ultrasound Robot: A Novel Imaging Concept and a Novel Motorized Kinematics for an Ultrasound Probe during Laparoscopic Interventions

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***Abstract*—In this manuscript we propose a robot with a novel kinematics and a novel imaging concept for a transcutaneous ultrasound probe. The underlying goal is to provide a laparoscopic surgeon intraoperative real-time images from within the surgical field without additional man power. The robot is manually controlled by the surgeon through a joystick console. The device is divided into two separate chambers. One is filled with pressurized water and incorporates an transcutaneous ultrasound probe. It is covered with a flexible silicone membrane that is in contact with the patient. The second cavity incorporates the kinematics and is filled with pressurized air. The kinematics has four degrees of freedom (two translational and two rotatory). In this paper, we provide the mathematical description for the direct as well as for the indirect kinematics along with a validation experiment.**

I. Introduction

Kidney cancer is one of the most common types of malign neoplasms. For Germany it is forecasted that there will be 15,100 malign tumors incidences (9,300 men; 5,800 women) in 2012. The relative 5-year survival rate is 74 % for men and 75 % for women [1]. Open intervention remains the gold standard therapy to cure the patient from this kind of disease [2]. However, laparoscopic partial nephrectomy (minimally invasive removal of the tumor at the kidney while preserving the function of the organ) has become a reliable option for many patients with tumors up to 7 cm [3] and its applicability is expected to even increase [4].

Laparoscopic interventions are performed with sticklike instruments (length 30 to 40 cm; diameter usually 5 mm) that are inserted into the abdomen of the patient through artificial orifices (trocars). The movements of an instrument are limited by its access, i.e., it can only be moved around a pivot point limiting the surgeon's possibilities to manipulate the surgical field. The abdominal cavity is inflated by carbon dioxide to provide the surgeon with enough space for movements of the instruments inside the patient body. Intraoperative imaging is performed by a specialized endoscope called a laparoscope. Nowadays, laparoscopes are employed in combination with a video camera that transmits the images from inside the patient to an external monitor in the surgeon's field of view [5], [6]. Endoscopes have in common that they almost only provide superficial information of the surgical field. Therefore, in the case of laparoscopic partial nephrectomy the surgeon lacks crucial information about the size and location of the tumor within the kidney as well as the layout of internal blood vessels. This may lead to a positive surgical margin (the tumor was not completely removed) or to unnecessary high blood lose if a major blood vessel is injured (the kidney is one of organs with the highest blood supply) [7]. Ultrasonography may overcome these problems by providing an internal view of the surgical field [7], [8]. It provides real-time images at reasonable costs without ionizing radiation. Applicable sonographic approaches could be performed with laparoscopic or transcutaneous ultrasound probes. Laparoscopic probes are inserted into the abdominal cavity through a trocar such as other laparoscopic instruments. Therefore, their motions are limited by this pivot point making it rather challenging for the surgeon to reach a good scanning position. If he wants to keep this specific position while resecting the tumor, an additional person is required to hold the probe, adding one more person to the already crowded operating room theater and increasing the cost of the operation. Both factors limit the use of laparoscopic ultrasound probes to few specialized centers. Transcutaneous probes need to be applied from the back of the patient since their ultrasonic waves are reflected by the gas bubble in the abdomen of the patient. Unreachable for the surgeon an assistant is required to guide the probe on the back of the patient. In addition to the reported drawbacks described for laparoscopic probes, this approach adds another layer of complexity for the surgeon: missing hand eye coordination. Hand eye coordination is an essential part of ultrasound imaging since it provides the user with additional information on the anatomical context. Thus, missing hand eye coordination makes the interpretation of sonographic images even harder.

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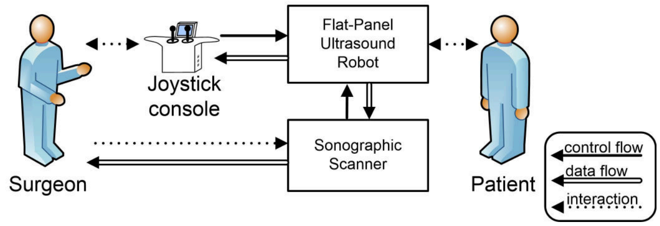

Fig. 1. Flow chart of the robotic system.

To overcome these problems a motorized kinematic could guide the sonographic probe, allowing the surgeon to control the scanning position of the probe without adding an additional person to the operating room theater. Several approaches to guide a sonographic probe have been proposed to the scientific community. Table I provides an overview on recently published concepts. However, each system has its own drawback as listed in the column "potential for improvements".

II. Flat-Panel Ultrasound Robot

Our goal is to provide the surgeon intraoperatively with sonographic images of the surgical field without the need for additional man power. To achieve this goal we investigated a concept for actuating a transcutaneous ultrasound (US) probe during laparoscopic partial nephrectomy that can be controlled by the surgeon. In detail we investigated a robotic concept:

1) that can be installed at side of the operating room table to scan the patient from its back (Flat-Panel Design). Thus, no additional space, required for the intervention, is consumed by the robot.
2) where the transmission medium of the sonographic waves is separated from the kinematic to avoid deposit.
3) with extended operating range by employing two rotatory degrees of freedom in combination with two translational degrees of freedom (DOF).

A. Static System Description

The building blocks of the robotic concept are included in the flow chart of Fig. 1. The surgeon controls the robot through a joystick console. The robot actuates a sonographic probe scanning the patient. The probe is connected to a sonographic scanner that displays its information to the surgeon. Fig. 2-a visualizes the robot installed at the side of the OR table consuming no absolutely essential space in the OR theater. The robot itself is separated into two different chambers as visualized by the sectional view 2-b. The lower chamber incorporates the kinematics and the electronics while the US probe with an US guiding liquid (water) resides in the upper chamber. Water is necessary since the longitudinal sound waves need a transmission medium to propagate. Additionally, the medium should have a similar acoustic impedance to human tissue to minimize the reflection of sound waves. Sound waves are reflected at the boundary layer between two materials, proportional to the change in the acoustic impedance *Z*. Fig. 2-a emphasizes how we want to expand the operating range of the robot by two additional rotatory DOF. With this mechanism the robot is able to scan even areas that are outside of the body of the robot. More details on the kinematic are provided in Fig. 3. The kinematics consists of two translational DOF (q_1, q_2) mounted in series with two rotatory DOF (q_3, q_4). The rotatory DOFs allow for a precession (q_3) and a pitch (q_4) motion of the sonographic probe. The pitch motion is implemented by a parallel kinematics with a remote center of motion (RCM). A RCM is required due to the limited space at the tip of the sonographic probe while built-in in the robot. The robot incorporates a commercial sonographic probe (convex array probe, 2,0 - 4,0 MHz, BK Medical, Herlev, Denmark) that is connected to the sonographic scanner (Flex Focus 400, BK Medical, Herlev, Denmark). The implementation of the robot is visualized in Fig. 4 along with detailed information on the characteristics of the robot in Table II.

B. Dynamic System Description

In the following we introduce a mathematic description of the robot's kinematic. To describe the position and orientation (pose) of the US probe with respect to the current motor position we first define the direct kinematics. To describe the position of the motors based on the current pose of the US probe we compute the inverse kinematics afterwards.

1) Direct Kinematics: For the description of the direct kinematics we employ the notation of Denavit-Hartenberg [13]. The coordinate systems of the robot's kinematic from which we derive the Denavit-Hartenberg parameters are visualized in Fig. 5. The following homogeneous transformation matrix describes the transformation from the *base* coordinate system of the robot (blue coordinate system in the lower left corner of the robot in Fig. 5-a) to the *tool center point (TCP)* coordinate system (blue coordinate system at the top of the US probe in Fig. 5-a)

$$ {}^{base}\mathbf{T}_{tcp} = \begin{bmatrix} & & & d_1 \\ & \mathbf{R} & & d_2 \\ & & & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

$$ \mathbf{R} = \begin{bmatrix} \cos\varphi_{z,base}\cos\varphi_{y,tcp} & -\sin\varphi_{z,base} & \cos\varphi_{z,base}\sin\varphi_{y,tcp} \\ \sin\varphi_{z,base}\cos\varphi_{y,tcp} & \cos\varphi_{z,base} & \sin\varphi_{z,base}\sin\varphi_{y,tcp} \\ -\sin\varphi_{y,tcp} & 0 & \cos\varphi_{y,tcp} \end{bmatrix} \tag{2} $$

where d_1 and d_2 denote the variable translation of q_1 and q_2. d_3 is the fixed distance between the coordinate systems of both rotatory DOF (q_3, q_4). $\varphi_{z,base}$ denotes the rotation of the z-axis of the *base* coordinate system introduced by q_3. $\varphi_{y,tcp}$ represents the rotation of the y-axis of the *tcp* coordinate system introduced by q_4.

2) Inverse Kinematics: In order to move the US probe to a given pose one must know the exact position for each motor at this pose, i.e., we need the inverse mathematical description of the kinematics. We derive the inverse kinematics from the direct kinematics defined above.

TABLE I
EXCERPT OF STATE OF THE ART OF MOTORIZED TRANSCUTANEOUS US PROBES.

source and system name	medical application	kinematic and mounting	sterilization concept	potential for improvement
Gumprecht *et al.* 2011 (Germany) [9], *Flat-Panel Ultrasound Manipulator (FP-USM)*	scanning of the kidney during laparoscopic interventions	2 translational DOF; installed in the operating room (OR) table	robot covered by sterile plastic film	deposit on the kinematics, limited operating range
Ito *et al.* 2010 (Japan) [10], *FASTele*	dectection of internal bleeding for mobile ambulance	circular-prismatic-joint remote center of motion; two rotatory DOF; contact pressure through mechanical spring; attached to the abdomen patient by belt	none	during lap. interventions the abdomen is blocked by the surgical instruments
Nakadate *et al.* 2010 (Japan) [11], *WTA-2*	reduce fatigue of the sonographic user	base system with 3 passive DOF carries a robot with 7 active DOF	none	no telemanipulation control only hands on
Vilichis-Gonzalez *et al.* 2007 (France, Mexico) [12], *TERMI*	venous thrombosis examination in lower members	circular prismatic joint remote center of motion; 3 DOF; mounted on base robot with three DOF	none	requires additional robotic arm
Fukuoka *et al.* 2006 (Japan)	mammography	2 translational DOF; kinematics built-in in a rollable table	none	not applicable for laparoscopic interventions

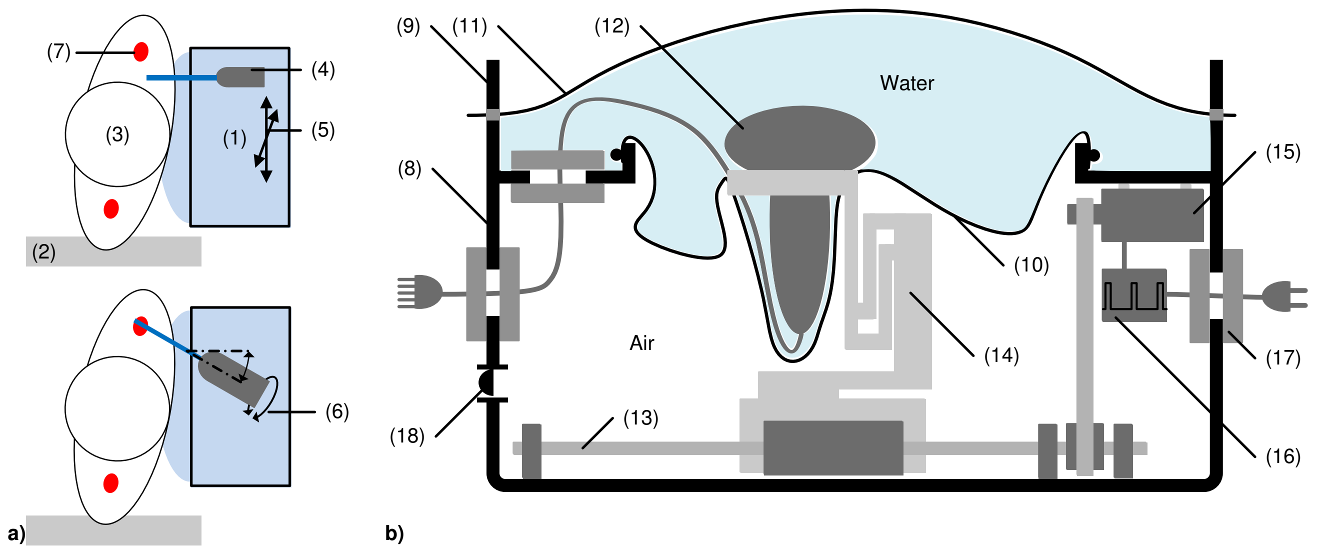

Fig. 2. a) The robot (1) is installed at the side of the operating room table (2). During the application the robot scans the patient (3) through his back. The ultrasound probe (4) may be moved translationally (5) in two DOF and rotatory (6) with pitch or precession movements to scan the target area (7), e.g., the kidney. b) Sectional view of the robot's basic concept, consisting of two separated, vertically aligned chambers. The upper cavity is filled with pressurized water and the lower one with pressurized air. The chambers are framed by a two-parts aluminum body (8), (9). The chambers are separated by a flexible PU membrane (10). The upper chamber is covered by a flexible silicone membrane (11) and incorporates the ultrasound probe (12). The lower chamber incorporates the kinematics with two translational DOF (13) and two rotatory DOF (14) to move the ultrasound probe. The linear DOFs are actuated by stepper motors (15) with a gear belt drive and the rotatory DOFs by servo motors. The kinematics is controlled by a microcontroller (16) that receives its control commands through a sealed cable channel (17). There are several valves (18) to insert / release water or air into / from the cavities of the robot.

TABLE II
FLAT-PANEL ULTRASOUND ROBOT CHARACTERISTICS (PFM: PULSE FREQUENCY MODULATION, PWM: PULSE WIDTH MODULATION).

DOF	name	type	actuator	operating range	resolution	control frequency	control mode	
							actuator's native	*implemented*
q_1	x-axis	linear	stepper motor	256 mm	0.2 mm	50 Hz	velocity (PFM)	position and velocity
q_2	y-axis	linear	stepper motor	125 mm	0.2 mm	50 Hz	velocity (PFM)	position and velocity
q_3	precession	rotatory	servo motor	180 °	1 °	50 Hz	position (PWM)	position and velocity
q_4	jaw	rotatory	servo motor	60 °	0.75 °	50 Hz	position (PWM)	position and velocity

$$q_3 = \varphi_{z,base} \quad (3)$$

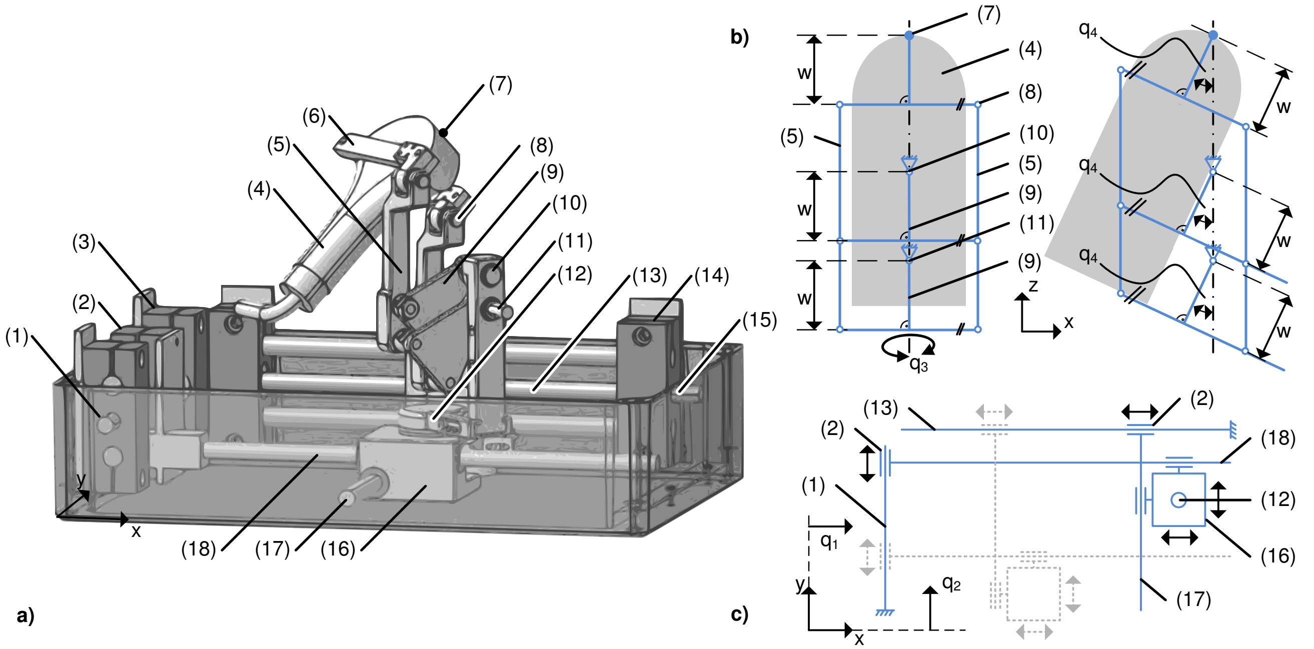

Fig. 3. Basic concept of the kinematics: a) The sonographic probe (4) is held by two jaws (6) that are attached to the parallel kinematics (5, 8-11), creating a remote center of motion at the tip of the probe (7) for pitch movements. The parallel kinematics consists of two parallel rods (5) that are supported by two parallel triangles (9). The triangles are mounted on a stand (10, 11). The shaft of the lower mount (11) is actuated by a servo motor through a gear belt transmission. A second rotatory DOF (12) rotates the whole pitch mechanism, moving the probe in a precession motion. It is also actuated by a servo motor with a gear belt drive. A kinematics with two translational DOF moves the rotatory DOFs. It consists of two bars (17, 18) that are connected through slide bearings at the interface (16) to the rotatory DOFs. Each bar is mounted on a spindle drive (1, 13) with shaft joints (2) that is attached to the body of the robot (3, 14). Each spindle is actuated by a stepper motor through a gear belt transmission (1, 15). b) The ultrasound probe (4) performs pitch movements at a remote center of motion (7), i.e., there is no joint at the center of the rotatory motion. This motion is achieved by a parallel kinematics that is visualized at two different displacements (left: no displacement, right: with displacement). The kinematics is supported by two stationary joints (10, 11). Two parallel triangles are connected (9) to the stationary joints. Two parallel rods (5) connect both triangles with the rotatory joints (8) close to the remote center of motion (7). c) The translational kinematics has one linear guiding for each DOF (1, 13), each with a prismatic joint (2). Attached to these joints are two rods (17, 18) actuating the interface to the rotatory DOF (16). The interface supports the slide bearing of joint q_3 (12). An alternative displacement is visualized by the light grey dotted illustration.

$$q_4 = \arctan\left(\frac{\tan(-\varphi_{x,base})}{\sin(\varphi_{z,base})}\right) = \arctan\left(\frac{\tan(\varphi_{y,base})}{\cos(\varphi_{z,base})}\right) \tag{4}$$

$\varphi_{x,base}$ denotes the rotation of the x-axis of the *base* coordinate system; identical for $\varphi_{y,base}$ and $\varphi_{z,base}$.

3) Controlling the Motors: The robot's DOF are actuated by different kinds of motors. While the translational DOF (q_1, q_2) are actuated by stepper motors, the rotatory DOF (q_3, q_4) are actuated by servo motors. These actuators require different control methods. A stepper motor only moves in the desired direction when it receives a motion pulse. Hence, its velocity depends on the frequency by which it receives a motion pulse. This control mode is called pulse frequency mode (PFM). In order to control the position of the employed stepper motors we equipped them with positioning sensors. For closed loop control we implemented a simple bang-bang controller since our stepper motors do not overshoot. The servo motors on the other hand accept only positioning commands via pulse width modulation (PWM). Pulse width modulation in our case means that we have to send the servo motors every 20 ms a positioning pulse with a length between 1 ms and 2 ms. The target position of the servo motor is encoded in the length of the pulse. A length of 1 ms is defined as the outer left position and a length of 2 ms is defined as the outer right position of the servo arm. The pulse may vary in steps of 1 ns providing us with a step size of 0,18° for a servo motor with an operating range of 180°. The velocity by which the servo motor approaches its target position cannot be controlled. In order to steer the servo motors in velocity control mode, we have to generate a custom trajectory by which the servo motor approaches its target position.

4) Integration in the Surgical Workflow and Sterilization Concept: Due to its integration into the OR room table the robot will have no effect on the surgical workflow. The robot will be installed before the patient is placed onto the table. The joystick console will be installed at the OR table next to the surgeon. Hence, the surgeon may control the robot whenever he wants to. For sterile use the robot and the joystick console are covered with a plastic film.

III. Validation Experiment

In an experiment we assessed if it is possible to scan the kidney of ten subjects (n = 10) with the ultrasound robot. The kidney of all subjects was visible as can be seen in Fig. 6. We could not detect a significant degradation in the quality of

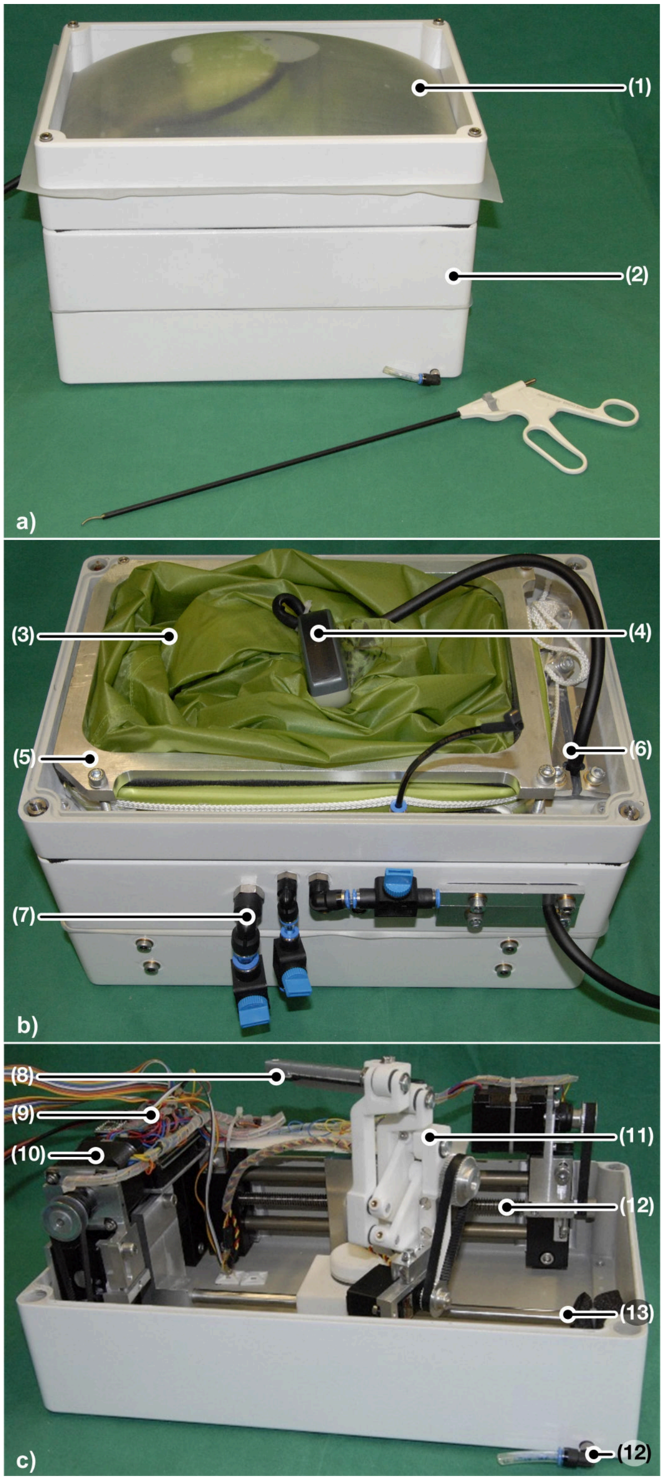

Fig. 4. Implementation of the robot: a) entire robot: (1) outer membrane, (2) housing of the robot, b) upper chamber opened: (3) inner membrane, (4) US probe, (5) flange of the inner membrane, (6) orifice of the US probe, (7) connections for air, water, power, and communication; c) view into the lower chamber with the kinematics: (8) jaws to hold the US probe, (9) control and power electronics, (10) stepper motor to actuate the x-axis, (11) rotational kinematics implemented with PA2200 through rapid prototyping, (12) spindle drive with shaft joints of the translational kinematics (y-axis), (13) rod of the x-axis to move the rotatory DOF, (12) security valve.

the ultrasound images. These observations support the results published by Gumprecht *et al.* in 2011 [14].

IV. Conclusion

In this manuscript we proposed a robot with a novel kinematics and a novel concept for a transcutaneous US imaging. Our goal was to provide a laparoscopic surgeon intraoperatively real-time images from within the surgical field without additional man power. During application the robot is installed at the side of the OR table while scanning the patient through its back. The robot is manually controlled by the surgeon through a joystick console. The device is divided into two separate chambers. One is filled with pressurized water and incorporates the US probe. It is covered with a flexible silicone membrane that is in contact with the patient. The second cavity incorporates the kinematics and is filled with pressurized air. The kinematic has four DOF (two translational and two rotatory). We provided the mathematical description for the direct as well as for the indirect kinematics in this paper. In a validation experiment we were able to successfully scan the kidneys of ten subjects with the robot. Future work will include the clinical evaluation of the system.

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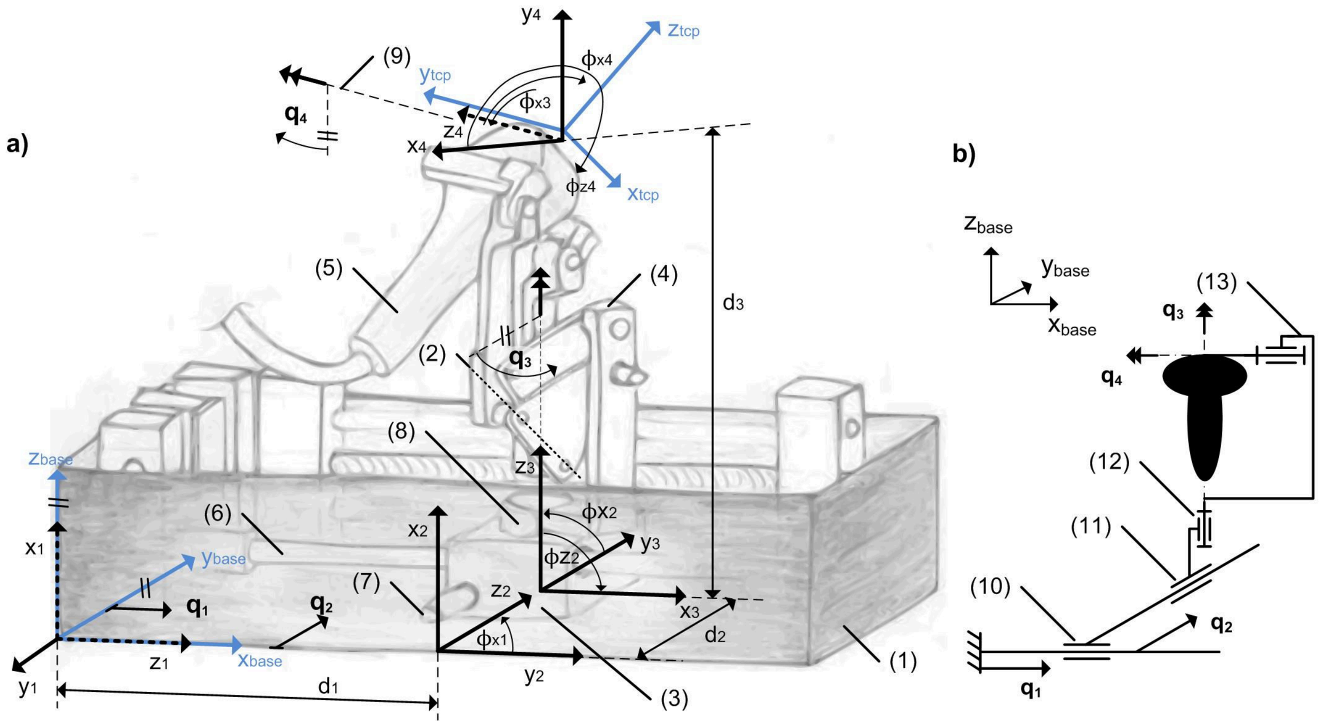

Fig. 5. a) Draft of the kinematics including its joints (G), flanges (V) and the Denavit-Hartenberg parameters of the robot: (1) body (basis, V0), (2) sledge of the spindle-linear table in x_{base}-direction (V1), (3) interface translational / rotational kinematics (V2), (4) supporting stand (V3), (5) US-probe (end effector, V4), (6) rod in $x_b ase$-direction (G1), (7) rod in y_{base}-direction (G2), (8) rotary foot of the supporting stand (G3), (9) rotary axis of the US-probe (G4). b) Model with a kinematic chain of joints and flanges of the kinematics visualized in a): (10) prismatic joint G1, (11) prismatic joint G2, (12) rotational joint G3, (13) rotational joint G4.

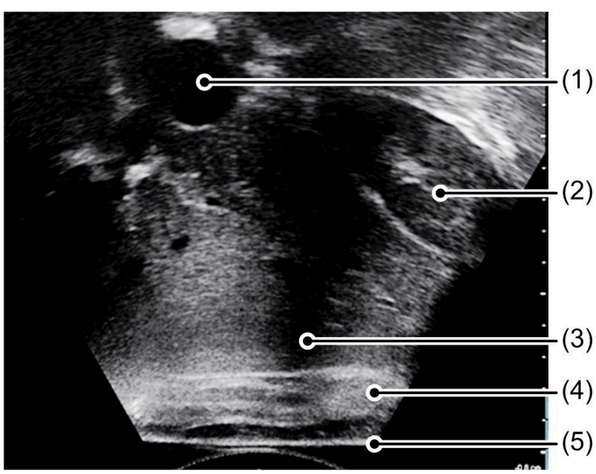

Fig. 6. Sample US image of a kidney (2) recorded with the flat-panel ultrasound robot (1) vena cava inferior, (3) acoustic shadows introduced by bone of the rips, (4) fat tissue, (5) flexible silicone membrane of the robot.

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