

# 6-Axis Hybrid Sensing and Estimation of Tip Forces/Torques on a Hyper-Redundant Robotic Surgical Instrument

Nural Yilmaz, Merve Bazman, Alaa Alassi, Berke Gur and Ugur Tumerdem

**Abstract**—In this paper a hybrid method for estimation of 6 degree-of-freedom (DOF) laparoscopic instrument tip force/torques in robotic-assisted minimally invasive surgery systems is proposed. The method is implemented on an in-house developed hyper-redundant (11-DOF) surgical robotic forceps prototype. This surgical robot is composed of two modules with a 7-DOF Kuka IIWA manipulator for performing 4-DOF Remote Centre of Motion (RCM) about the trocar and an articulated 4-DOF parallel wrist/gripper mechanism attached to the distal end of the Kuka robot for intra-corporeal manipulation. The hybrid sensor-based/sensorless method fuses torque estimates from the parallel wrist mechanism with measurements from a force sensor attached between the wrist base and the Kuka tool frame. With this approach it is possible to obtain force/torque estimates on all Cartesian axes (x, y, z, yaw, pitch, roll) of the forceps tip. The prototype is one of the first systems designed for robotic surgery that can achieve accurate force estimation on all 6 axes of the instrument tip. Experiment validation results with a force sensor verify the efficacy of the proposed method.

## I. INTRODUCTION

Robotic-assisted minimally invasive surgery (RAMIS) systems are teleoperation systems enabling surgeons to remotely control robotic laparoscopic instruments inserted into the patient body through small incisions. They come with certain advantages over conventional laparoscopic/minimally invasive surgery systems such as enabling the surgeon to retain the wrist bending capability in the patient body (intra-corporeally), providing the means to overcome the fulcrum effect in conventional laparoscopic surgery through motion mirroring, hand motion scaling to achieve more accurate control, and hand tremor filtering in addition to providing a more ergonomic means of performing the operation while being seated. The first of the RAMIS systems, that was able to achieve these features, is the da Vinci Surgical System by Intuitive Surgical. The da Vinci system has an architecture that has been repeated by most other RAMIS systems. It has two master control interfaces with 8 degrees-of-freedom (DOF) and two slave robotic forceps systems with 7-DOFs, in addition to two slave robots holding the laparoscopes. The robotic forceps system consists of a 4-DOF remote centre of motion mechanism (RCM) capable of

performing rotations about and translation along the incision point thus enabling the positioning of the forceps wrist. A miniature wrist mechanism of 3-DOF, serially articulated to the RCM mechanism, achieves 2-axis intra-corporeal bending and gripping motions, mimicking the articulation of the human hand within the body. To achieve these motions while being actuated extra-corporeally a pulley-cable transmission system has been utilized. This results in a tradeoff as cable actuated mechanisms result in decreased precision [1], and force feedback, due to nonlinearities such as cable slip, slack and stretch as well as high friction in the system. Due to low quality force feedback, this feature has been deactivated in the da Vinci system [2], and this is a major drawback of RAMIS systems [3], [4].

Many researchers have tried to improve force feedback in the da Vinci system and/or similar RAMIS systems. In order to achieve this, accurate force sensing or estimation is required. Some researchers have tried to implement force sensors on the robotic slave system [5], [6], [7]. In this approach, the force sensors are mounted on the extra-corporeal RCM part of the robot due to the large size of the sensors. Two force sensors can be used in tandem to estimate and filter the interaction forces of the robot with the trocar sleeve planted at the incision. However, this method is unable to provide estimates on the wrist bending torques within the body. In [8], a force sensor attached to the jaws of the gripper of the Raven II surgical system enables intra-corporeal force sensing in x, y, z, and gripping axes. One of the smallest force 6 axis force/torque sensors in the world has been developed in [9] for the MICA/MIRO robotic surgery system to achieve force sensing in 6-DOFs including the wrist axes.

Another approach to force feedback has been to estimate the forces acting on the slave system from actuator signals rather than using force sensors. The first example of such estimation was [10] from the RCM part of the Black Falcon Surgical robot for 3-DOF Cartesian x, y, z force sensing. In [11], an estimation method called the Sliding Mode Perturbation observer is utilized to estimate grasping forces on the da Vinci Endowrist system. Sang et al. [12] reported accurate x, y, and z Cartesian force measurements on the da Vinci Research Kit by utilizing parameter identification and joint current measurements. A novel decoupled cable driven wrist was proposed in [13] and pitch-yaw torque estimation was reported. Haghighipanah et al. [14] highlighted that loss or variance of cable tensions is a major obstacle in force estimation. In the same paper, a cable tension estimator is also proposed to improve the force estimation from an extra-

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corporeal axis of the Raven II system.

Different transmission types are proposed for the wrist and gripper mechanisms of the RAMIS systems to eliminate the problems of pulley-cable systems. In [15], a 4-DOF pneumatic forceps wrist and a single axis force estimation method from cylinder pressures was proposed. A 3-DOF rigid link mechanism was proposed in [16] with 70 degree and 50 degree bending capability on the pitch and yaw axes, respectively. However, force sensing is achieved on grasping, pitch, and yaw axes with strain gauges placed on the rigid push-pull rods. In [17] another rigid link mechanism was proposed and a load cell used in the extra-corporeal transmission part to achieve force sensing in the grasping axis. In [18] and [19] a 3-DOF parallel rigid link wrist mechanism capable of two axis  $\pm 90$  degree bending and thrust motions, and a disturbance observer based force/torque sensing method for rigid link wrist mechanisms was proposed. In [20] this wrist mechanism was integrated with a Kuka LWR IIWA manipulator to have 7-DOFs.

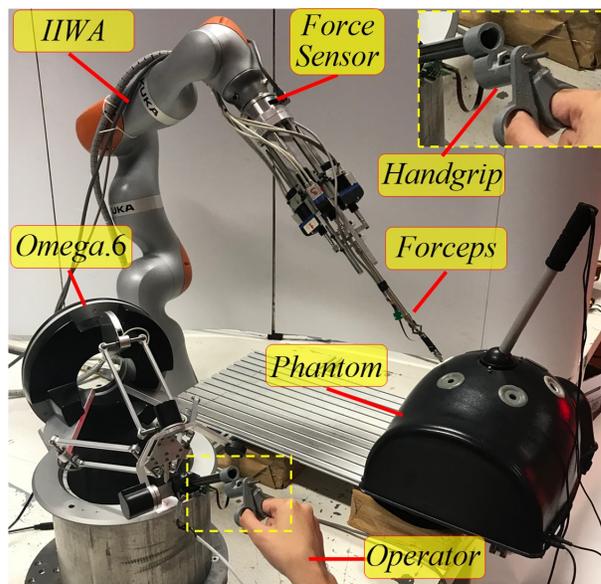
To the best of our knowledge, at the time of writing, the MIRO system reported in [9] is the only 6-DOF force feedback capable system in the world. However, the MIRO system requires the attachment of a miniature force sensor to the instrument tip, which increases the costs of the instruments that have to be often replaced. In this paper, a 6-DOF hybrid force estimation/sensing method is presented for the Kuka LWR/wrist combined mechanism reported in [20]. The method uses hybrid force estimation using disturbance observers for the intra-corporeal wrist and gripper part, and force sensing from a 6 axis force/torque sensor mounted extra-corporeally on the Kuka manipulator. These measurements/estimates are then combined to obtain 6-axis force sensing (Cartesian  $x, y, z$ , and pitch, yaw, roll) from the tip of the instrument. With this approach, 6-DOF force sensing is achieved without the use of expensive force sensors that need to be attached to the replaceable tip of the instrument. Furthermore, the proposed approach represents a step towards completely sensorless 7-DOF force sensing in surgical robotics. This approach can also be utilized for other modular RCM/wrist mechanisms to combine force sensing/estimation measurements from the wrist and RCM parts individually.

The composition of this paper is as follows: Section II describes the instrument wrist and the manufactured prototype, Section III describes the proposed external force estimation method, Section IV presents experiment results, and the paper is concluded in Section V.

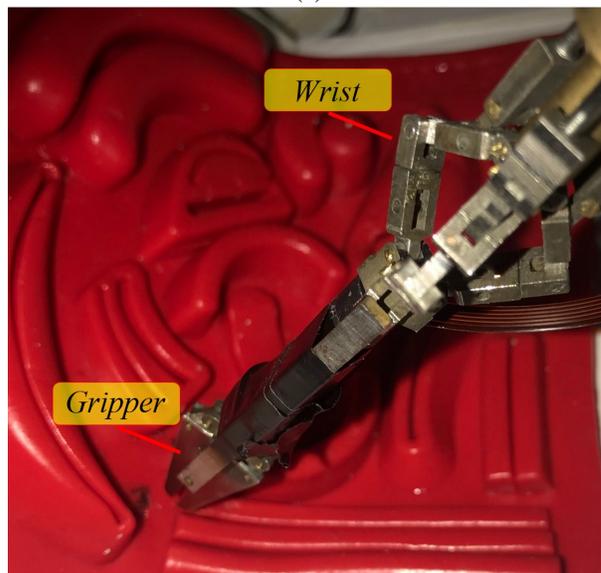
## II. THE SURGICAL ROBOT SYSTEM OVERVIEW

The surgical robot system consists of 3 main parts: the master, the slave manipulators, and the control and communication system that links the master and slave systems together.

The slave manipulator makes use of a 11-DOF surgical robot system [20] that is a combination of a novel



(a)



(b)

Fig. 1: Visualization of the proposed hyper-redundant surgical robot system

wrist/gripper mechanism and 7-DOF Kuka IIWA 7 R800 robot. Intra-corporeal bending and gripping motions are realized by the 4-DOF robotic forceps mechanism that is a combination of a gripper and a 3-DOF parallel wrist mechanism first proposed in [18]. The 4-DOF RCM is performed by the redundant 7-DOF IIWA manipulator to accurately change the wrist position within the patient. Detailed design and the kinematic analysis can be found in [20]. This paper focuses on a force estimation algorithm developed for this system and similar modular RCM/articulated wrist units. Typically, all RAMIS forceps mechanisms make use of such modular RCM/wrist units connected in series (macro-micro approach). The system used in this paper is hyper-redundant

whereas most systems utilize only 7-DOFs and the method we propose can be utilized in any other redundant systems.

In the master side, a Omega.6 haptic command interface is used by the surgeon/operator to generate a reference trajectory composed of translational and rotational position signals for the slave manipulator. In addition, an in-house developed handgrip mechanism is mounted to the Omega.6's stylus to control the opening and closing motion of the slave gripper.

The real-time communication system between master and slave robots is also made up of 2 subsystems which handle bidirectional communication with 1) Omega.6, IIWA, and force/torque sensor 2) 4-DOF forceps and handgrip mechanisms. The real-time programming of the first and second subsystems are C++ and Matlab/Simulink based, respectively. Both subsystems communicate with each other through a UDP based client-server model. In addition, the computations regarding kinematic solution and force estimation are realized in the second subsystem which is entirely based on the QUARC real-time software [21].

### III. 6-DOF FORCE ESTIMATION

The 6-DOF force estimation algorithm also contains two subsystems. The first subsystem is the force measurement module (force/torque sensor) attached between the wrist/gripper mechanism and the Kuka tool tip and the second subsystem is the sensorless torque estimation algorithm running on the wrist/gripper subsystem making use of joint current references and encoder measurements. The proposed 6-DOF estimation algorithm fuses the output of the two subsystems based on the configuration and the Jacobian of the combined surgical robot.

External force/torques  $\tau_{ext}$  on joints result from external end-effector force/torques  $F_{ext}$  and are related to  $F_{ext}$  by

the Jacobian of the manipulator  $J(q)$ .

$$\tau_{ext} = J^T(q) \cdot F_{ext} \quad (1)$$

In general, elements of the end-effector force/torques in Cartesian space are defined as,

$$F_{ext} = [F_x \ F_y \ F_z \ \tau_x \ \tau_y \ \tau_z]^T \quad (2)$$

The Virtual Trocar Method presented in [20] provides a way for reducing the 11 combined DOF surgical robot consisting of 7-DOF IIWA manipulator and the 4-DOF wrist/gripper mechanism to 6-DOF (excluding the gripper). This approach also simplifies force estimation because it reduces the complexity of the Jacobian. Once the 11-DOF combined surgical robot is reduced to the 6-DOF virtual trocar robot (a virtual robot that has a base at the trocar location as shown in figure 2), IIWA end-effector and wrist/gripper forces and torques are utilized to find the joint force and torques of the virtual trocar robot. According to the Virtual Trocar Method, virtual joint variables are defined as,

$$q = [\phi \ \psi \ \rho \ \gamma \ \alpha \ \beta]^T \quad (3)$$

where  $\phi$ ,  $\psi$ ,  $\rho$  and  $\gamma$  are provided by IIWA manipulator,  $\alpha$  and  $\beta$  are provided by the wrist/gripper mechanism. Similarly, joint force/torques vector of the virtual trocar robot is,

$$\tau = [\tau_\phi \ \tau_\psi \ F_\rho \ \tau_\gamma \ \tau_\alpha \ \tau_\beta] \quad (4)$$

Here,  $\tau_\alpha$  and  $\tau_\beta$  are external torques applied at the center of the wrist mechanism and they are estimated using the proposed method in [19]. The computation of the joint force/torque vector of the Virtual Trocar Robot is further explained in the following subsections.

#### A. IIWA Manipulator

The  $6 \times 1$  IIWA Cartesian force-torque vector acting at the Kuka end-effector ( ${}^I E F$ ) is measured by a 6-DOF force/torque sensor (ATI/Schunk Delta SI-330-30). The Kuka

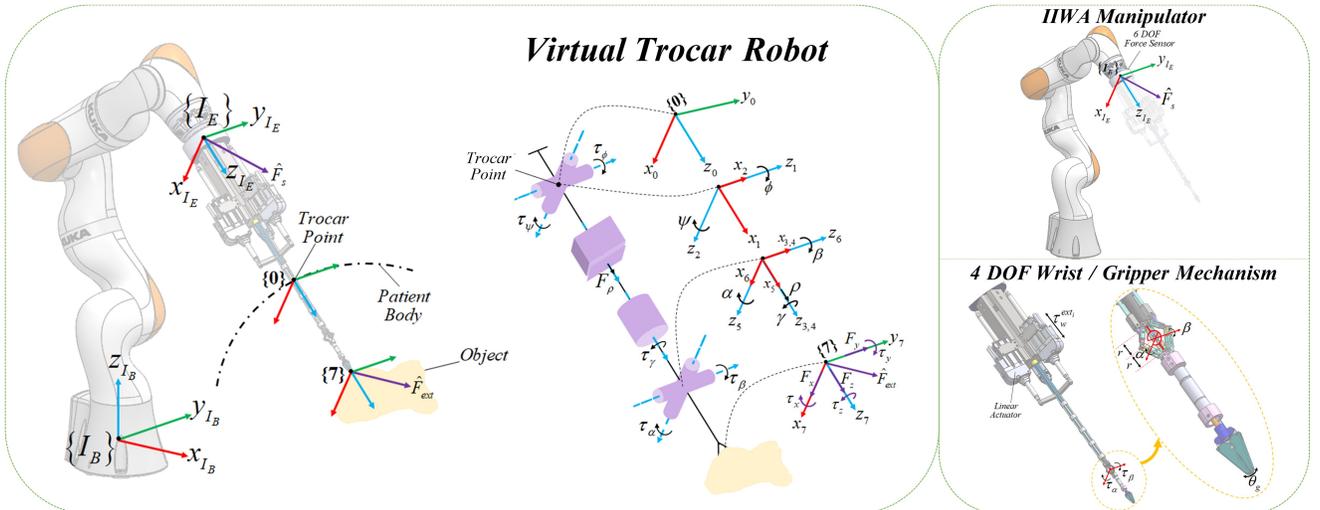


Fig. 2: A schematic depicting the virtual trocar robot and the frames

system does provide joint torque estimates which can be mapped to the end-effector forces. However, force estimates provided by the Kuka system are not accurate and cannot be used for sensorless force/torque estimation of the tip forces without further modifications when the wrist module is attached to the Kuka. For this reason, a 6-DOF force sensor is mounted between IIWA end-effector and forceps mechanism such that the frame on sensor is coincident with  $I_E$  and, that forces/torques exerted on the IIWA end-effector are measured via the attached sensor. Provided that the Kuka joint torque estimation problems can be solved, the complete estimation algorithm can become sensorless.

### B. 4-DOF Wrist/Gripper Mechanism

On the wrist/gripper mechanism side, sensorless force estimation is realized based on an algorithm proposed in [19]. The method utilizes a novel reaction force observer (RFOB) in joint space, which is a modified disturbance observer (DOBS) combined with Neural Networks (NN) for inverse dynamics compensation. External force/torque estimation in Cartesian space is achieved by the use of the robot Jacobian.

As an improvement over [19], the wrist mechanism is trained as the end-effector position of IIWA manipulator with respect to frame  $\{0\}$  is changed to provide the wrist torque estimator, which makes use of a NN, with a training dataset to teach disturbance forces due to the inverse dynamics in different Kuka configurations. The reason for this is that disturbance forces on the wrist change when the configuration of the Kuka changes as it moves during RCM operations. After the training, the external torques acting on the wrist end-effector  $\{\tau_\alpha, \tau_\beta\}_w$  are calculated as given in [19], by subtracting the NN disturbance (inverse dynamics) estimates from the total disturbance estimates.

In the Neural Network structure, there are 9 inputs which are IIWA end-effector positions in x, y, z axes, positions and velocities of each motor of the wrist mechanism and 3 output neurons which represent disturbance forces acting on each wrist motor. 20 hidden neurons are chosen to associate inputs and outputs. Figure 3 shows the training, and estimation algorithm for the wrist axis and the dynamic equation in joint space can be written as:

$$M(q)\ddot{q} + C(q, \dot{q}) + G(q) + \tau_w^d + \tau_w^{ext} = \tau_w \quad (5)$$

where  $q, \dot{q}, \ddot{q}$  are respectively the vector of joint position, velocity and acceleration,  $M(q)$  is the mass matrix,  $C(q, \dot{q})$  and  $G(q)$  represent the vector of centrifugal and Coriolis forces and gravity terms, respectively;  $\tau_w^{ext}$  denotes the vector of external forces exerted on joints and  $\tau_w$  is the vector of forces supplied by joint actuators,  $\tau_w^d$  represents all other unmodeled forces, such as friction, unknown disturbances caused by nonlinear uncertainties. During collecting data for training procedure,  $\tau_w^{ext}$  is not applied on the system and the surgical robot is moved in free-space. Thus,  $\tau_w$  in (5) represents the internal dynamic forces in joint space.

TABLE I: DH parameters of the Virtual Trocar Robot

Joint	$\theta_i$	$d_i$	$\alpha_{i-1}$	$a_{i-1}$
1	$-\pi/2 + \phi$	0	$-\pi/2$	0
2	$-\pi/2 + \psi$	0	$-\pi/2$	0
3	0	$\rho$	$-\pi/2$	0
4	$\gamma$	0	0	0
5	$\pi/2 + \alpha$	0	$\pi/2$	0
6	$\pi/2 + \beta$	0	$\pi/2$	0
7	0	$D$	$\pi/2$	0

The sensorless force estimation procedure of the forceps mechanism is shown in Fig.3. In RFOB part, external forces are calculated by subtracting NN output ( $\tau_w$ ) which considers friction forces, unknown disturbances, interactive forces (inertial, centrifugal and Coriolis) and gravitational forces from total disturbance forces which are estimated by DOBS:

$$\tau_w^{ext} = \tau_w^{dis} - \tau_w \quad (6)$$

In final step, the estimated external forces exerted at the center of the wrist mechanism are found by premultiplying joint forces by the inverse of the wrist Jacobian ( $J_w$ ) transpose,

$$\widehat{F}_w^{ext} = J_w^{-T} \widehat{\tau}_w^{ext} \quad (7)$$

### C. Integration of IIWA and the Wrist Mechanism

Integration steps of IIWA and the wrist mechanism including all the transformations required for the force and position mapping can be seen in Fig.4. In order to find external forces acting on the end-effector of the Virtual Trocar Robot in Cartesian space, Jacobian matrix of the surgical robot excluding grasping axis is generated through relations between joint and Cartesian space velocities as explained in (1). For this purpose, the velocity of each link can be calculated by propagating them iteratively from the robot base to end-effector. The angular velocity and the linear velocity of the link  $\{i + 1\}$  are calculated with respect to frame  $\{i + 1\}$  depending on joint type. If joint  $\{i + 1\}$  is revolute:

$${}^{i+1}\omega_{i+1} = {}^{i+1}R^i \dot{\omega}_i + \dot{\theta}_{i+1} {}^{i+1}\widehat{Z}_{i+1} \quad (8)$$

$${}^{i+1}v_{i+1} = {}^{i+1}R^i ({}^i v_i + {}^i \omega_i \times {}^i P_{i+1}) \quad (9)$$

If joint  $i + 1$  is prismatic:

$${}^{i+1}\omega_{i+1} = {}^{i+1}R^i \omega_i \quad (10)$$

$${}^{i+1}v_{i+1} = {}^{i+1}R^i ({}^i v_i + {}^i \omega_i \times {}^i P_{i+1}) + \dot{d}_{i+1} {}^{i+1}\widehat{Z}_{i+1} \quad (11)$$

To find (4), IIWA end-effector and wrist/gripper forces and torques are utilized since the system is a combination of 7-DOF IIWA and 4-DOF wrist mechanism.  $\tau_\phi, \tau_\psi, F_\rho$  and  $\tau_\gamma$  are provided by IIWA,  $\tau_\alpha$  and  $\tau_\beta$  are provided by the integrated robotic wrist, and as a result these torques/forces can be mapped accordingly. In order to achieve this mapping we first make use of the frame transformations obtained from the DH parameters as can be seen in Table I.

Let  ${}^j T_i$  be the transformation matrix, which transforms the description in frame  $\{i\}$  to frame  $\{j\}$ . Further, for necessary

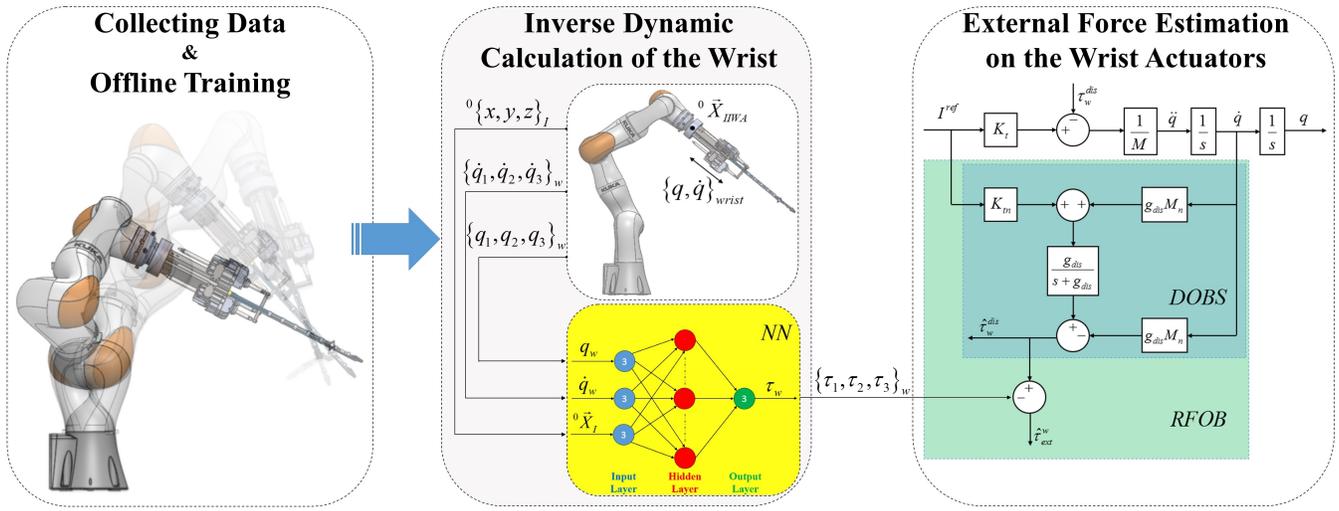


Fig. 3: Force estimation on the wrist mechanism

transformations in force estimation,  $I_B$ ,  $I_E$ , 0, 4 and 7 are defined as the IIWA base and IIWA end-effector coordinate frames, trocar frame,  $4^{th}$  and end-effector frames of the virtual trocar robot, respectively as can be seen in Fig.2.

6x1 force vector  $I_E F_s$  written in terms of  $I_E$  is transformed into  $\{4\}$  multiplying by 6x6 transformation matrix for the purpose of computing the first 4 trocar robot joint force and torques,

$${}^4F_s = \begin{bmatrix} I_E R & 0 \\ {}^4P_{I_E ORG} \times I_E R & I_E R \end{bmatrix} I_E F_s \quad (12)$$

where the cross product is understood to be the matrix operator

$${}^4P_{I_E ORG} = \begin{bmatrix} 0 & -{}^4P_{I_E ORG_z} & {}^4P_{I_E ORG_y} \\ {}^4P_{I_E ORG_z} & 0 & -{}^4P_{I_E ORG_x} \\ -{}^4P_{I_E ORG_y} & {}^4P_{I_E ORG_x} & 0 \end{bmatrix} \quad (13)$$

and (12) may be written compactly as

$${}^4F_s = I_E {}^4T I_E F_s \quad (14)$$

where  $I_E {}^4T$  is a 6x6 force-torque transformation matrix that can be expressed as the product of the transforms,

$$I_E {}^4T = {}^4T I_E {}^0T \quad (15)$$

Here,  ${}^4T$  is calculated using DH parameters given in Table-I and  $I_E {}^0T$  can be computed as,

$$I_E {}^0T = \left( I_B {}^0T \right)^{-1} I_B T \quad (16)$$

with  $I_B T$  in the equation representing a transformation matrix composed of IIWA DH parameters and a constant transformation matrix  $I_B {}^0T$  depending on initial configuration angles of the IIWA.

Therefore, to find the joint torques and the force acting on the first 4 DOFs ( $\tau_{0-4} = [\tau_\phi \ \tau_\psi \ F_\rho \ \tau_\gamma]^T$ ),  ${}^4F_s$  vector found

in (12) is multiplied by the Jacobian transpose with respect to  $\{4\}$  is required.

$$\tau_{0-4} = ({}^4J^T) {}^4F_s \quad (17)$$

where  ${}^4J$  is the 6x4 Jacobian matrix:

$${}^4J = \begin{bmatrix} -\rho c_\psi s_\gamma & -\rho c_\gamma & 0 & 0 \\ -\rho c_\psi c_\gamma & \rho s_\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ c_\psi c_\gamma & -s_\gamma & 0 & 0 \\ -c_\psi s_\gamma & -c_\gamma & 0 & 0 \\ -s_\psi & 0 & 0 & 1 \end{bmatrix} \quad (18)$$

Finally, the virtual trocar robot end-effector force vector ( ${}^7F$ ) is found by using the Jacobian that can be seen in (20) written in frame  $\{7\}$ ,

$${}^7F = ({}^7J^{-T}) \tau \quad (19)$$

where  $\tau$  includes both  $\tau_{0-4} = [\tau_\phi \ \tau_\psi \ F_\rho \ \tau_\gamma]^T$  and the estimated wrist torques occurring at the center of the wrist mechanism that are  $\tau_\alpha$  and  $\tau_\beta$ .

#### IV. EXPERIMENTS AND RESULTS

For the purpose of validation force/torque estimates on 6-DOF surgical robot system, a 1-DOF force sensor (Burster 8524) for the forces in x, y, z axes and uniform objects whose weights are known for the torques were used as seen in Fig.5. Each validation experiment was carried out separately. In the beginning of the experiments performed using force sensor, end-point of the robot was in contact with the force sensor and a small motion was given in the direction of validation axis after starting to the experiment. Then, the force value coming from sensor and the estimated value were compared. In torque validation experiments, uniform object whose mass is 0.05 kg was hung to the end-effector of the robot in x and y axes as seen in Fig.5(d,e). The mass causes a torque at the center of the wrist so that the last frame  $\{7\}$  on the robot was moved to the center of the wrist mechanism for the

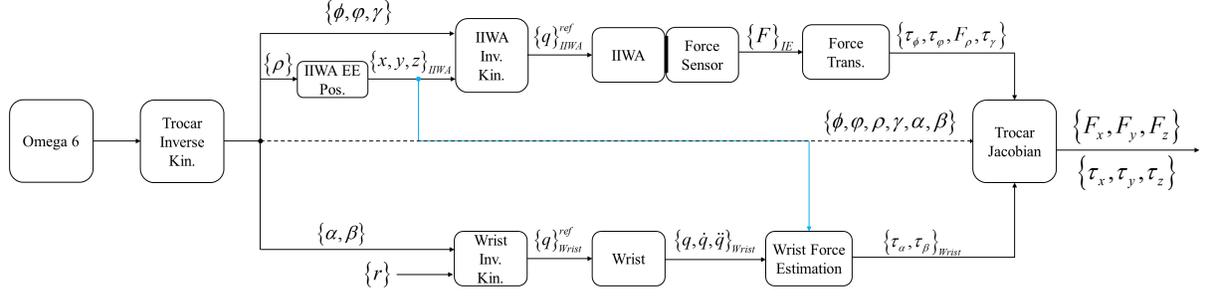


Fig. 4: Integration of IIWA and the Wrist Mechanism

$${}^7 J = \begin{bmatrix} -\rho c_\psi s_\gamma s_\alpha s_\beta + \rho c_\psi c_\gamma c_\beta + D(c_\psi c_\gamma c_\alpha - s_\psi s_\alpha) & -\rho(c_\gamma s_\alpha s_\beta + s_\gamma c_\beta) - D s_\gamma c_\alpha & -c_\alpha s_\beta & D s_\alpha & 0 & D \\ -\rho c_\psi s_\gamma c_\alpha - D(c_\psi c_\gamma s_\alpha s_\beta + c_\psi s_\gamma c_\beta + s_\psi c_\alpha s_\beta) & -\rho c_\gamma c_\alpha + D(s_\gamma s_\alpha s_\beta - c_\gamma c_\beta) & s_\alpha & D c_\alpha s_\beta & -D c_\beta & 0 \\ \rho c_\psi s_\gamma s_\alpha c_\beta + \rho c_\psi c_\gamma s_\beta & \rho c_\gamma s_\alpha c_\beta - \rho s_\gamma s_\beta & c_\alpha c_\beta & 0 & 0 & 0 \\ c_\psi c_\gamma s_\alpha s_\beta + s_\psi c_\alpha s_\beta + c_\psi s_\gamma c_\beta & -s_\gamma s_\alpha s_\beta + c_\gamma c_\beta & 0 & -c_\alpha s_\beta & c_\beta & 0 \\ c_\psi c_\gamma c_\alpha - s_\psi s_\alpha & -s_\gamma c_\alpha & 0 & s_\alpha & 0 & 1 \\ -c_\psi c_\gamma s_\alpha c_\beta - s_\gamma c_\alpha c_\beta + c_\psi s_\gamma s_\beta & s_\gamma s_\alpha c_\beta + c_\gamma s_\beta & 0 & c_\alpha c_\beta & s_\beta & 0 \end{bmatrix} \quad (20)$$

validation and the estimated torque and applied torque were compared at that point. For the validation in z axis, a thin rod was mounded to the end-point of the robot and a 0.04kg mass was hung at a distance of 7cm from the starting point

of the rod as seen in Fig.5(f). Thus, a torque was generated at the forceps tip z axis and the estimated torque and the computed torque were compared. In all experiments, joint variables of the trocar robot are defined as  $\phi = 0^\circ$ ,  $\psi = 0^\circ$ ,

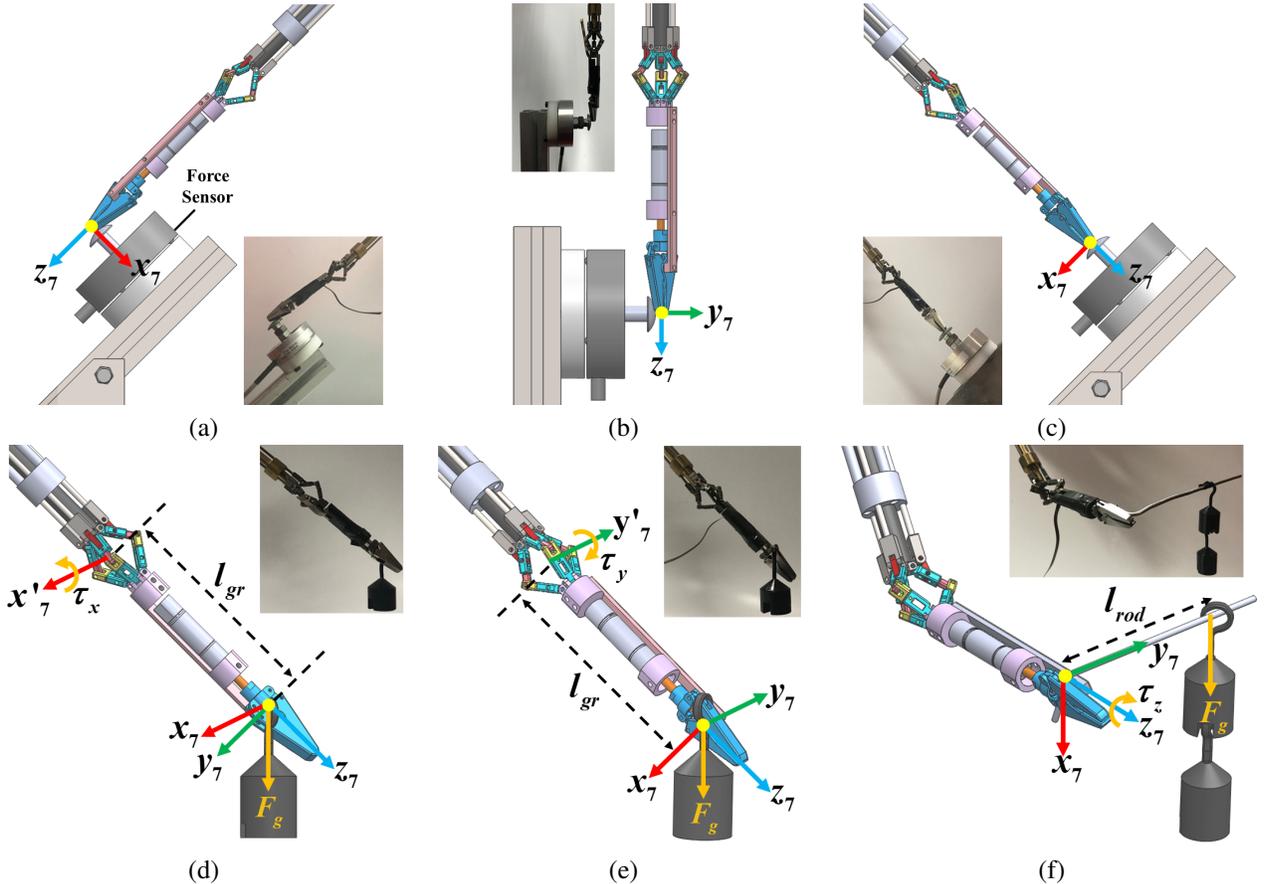


Fig. 5: Experiment setups (a)  $F_x$  (b)  $F_y$  (c)  $F_z$  (d)  $\tau_x$  (e)  $\tau_y$  (f)  $\tau_z$

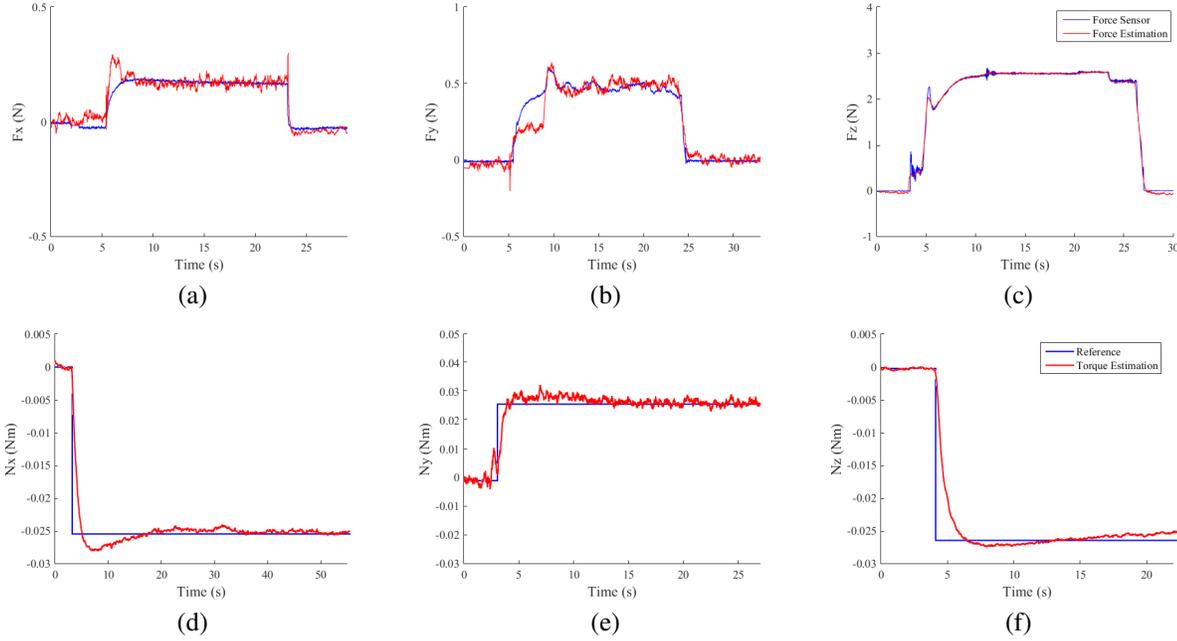


Fig. 6: Force/Torque validation results (a)  $F_x$  (b)  $F_y$  (c)  $F_z$  (d)  $\tau_x$  (e)  $\tau_y$  (f)  $\tau_z$

TABLE II: RMS error values during contact in force/torque validation experiments

F/T	$F_x$	$F_y$	$F_z$	$\tau_x$	$\tau_y$	$\tau_z$
RMSE (%)	5.4412	3.4145	0.0833	0.1172	0.4573	0.0771
RMSE N/Nm	0.0450	0.0083	0.0637	0.0009	0.0018	0.0070

$\rho = 0.083m$ ,  $\gamma = 0^\circ$ ,  $\alpha = 0^\circ$  and  $\beta = 0^\circ$ . Unlike these values, only  $\gamma$  in  $\tau_x$  and  $\beta$  in  $\tau_z$  validation experiments are selected as  $-90^\circ$  and  $-45^\circ$ , respectively. Experiment results show that the estimated forces/torques were highly accurate with RMS percent error (%RMSE) values of %5.4412 in  $F_x$ , %3.4145 in  $F_y$ , %0.0833 in  $F_z$ , %0.1172  $\tau_x$ , %0.4573 in  $\tau_y$  and %0.0771 in  $\tau_z$  as given in Table II.

## V. CONCLUSION

This paper has proposed a hybrid 6 axis force/torque estimation algorithm for a hyper-redundant surgical robot. This algorithm is tested on a commercially available Kuka IIWA robot and an in-house built wrist/gripper mechanism combined in macro-micro architecture. The experiment results show that tip forces/torques can be accurately estimated with the proposed method. The algorithm used here can also be applied to other surgical robot systems that may or may not be redundant with some modifications. Furthermore, with a completely in-house built system fully sensorless force estimation can be also be achieved. The neural network based reaction force observer can also filter out the trocar interaction forces, if the training is performed in contact with the trocar on the patient body.

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