Da Vinci research kit: PSM and MTM dynamic modelling

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I. Introduction

The DVRK is currently used by 26 research groups around the world [1]. The platform consists of two patient side manipulators (PSMs), one endoscopic manipulator and two master tool manipulators (MTMs). The Johns Hopkins University [2] provides a full ROS-based open controller of all the DVRK robotic arms. The controller allows position, velocity and current control and thus opens the way for developing and testing advanced control techniques. However, some control techniques, e.g. impedance-force control, realistic dynamic simulations and sensor-less strategies for collision detection or contact force estimation, requires an accurate knowledge of the robots dynamic models.

The aim of this work is to derive a complete dynamic model of both the MTMs and the PSMs arms of the DVRK system and use state of the art methods to obtain accurate identification of the dynamic parameters. In the case of the DVRK robot the presence of a 1-DOF double parallelogram and a counterweight in the PSM, and of a 2-DOF parallelogram in the MTM make the model complex and require a detailed discussion. A constrained optimization approach based on LMIs has been adopted to guarantee physical consistency of the dynamic parameters. The results of the experimental validation of the identified models are satisfactory, especially for the PSM, although they could be further improved.

II. DVRK dynamic modelling

In this section the dynamic models of both the PSM and MTM are presented. The computation of the dynamic model of the PSM arm can be performed using, e.g., the recursive Newton-Euler approach. The classical version of the algorithm for open kinematic chains must be suitably modified to include additional dynamic effects, as reported in details in the next sections. Thus the Newton-Euler algorithm, allows computing the vector of the joint torques $\boldsymbol{\tau}$ taking into account the inertia, Coriolis, centrifugal and gravity generalised forces. The contributions due to joint friction and to elastic forces acting on some of the joints can be added separately, i.e.:

$$\boldsymbol{\tau}_{ARM} = \boldsymbol{\tau} + \boldsymbol{\tau}_f + \boldsymbol{\tau}_e \tag{1}$$

where the friction contribution $\boldsymbol{\tau}_f$ has been set as the sum of viscous and static friction:

$$\boldsymbol{\tau}_f = \boldsymbol{F}_v \dot{\boldsymbol{q}} + \boldsymbol{F}_s \mathrm{sgn}\,(\dot{\boldsymbol{q}}) \tag{2}$$

and the elastic contribution $\boldsymbol{\tau}_e$ models the elastic forces acting on some joints.

$$\boldsymbol{\tau}_e = \boldsymbol{K}_e \boldsymbol{q} \tag{3}$$

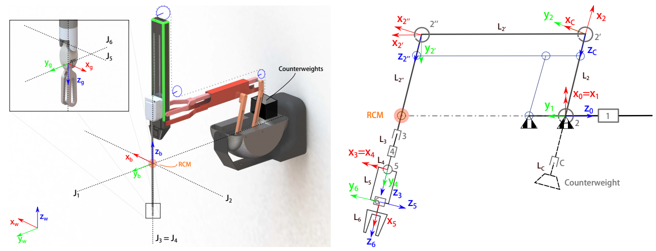

Fig. 1. Schematic of the PSM kinematics with the Denavit-Hartenberg frames

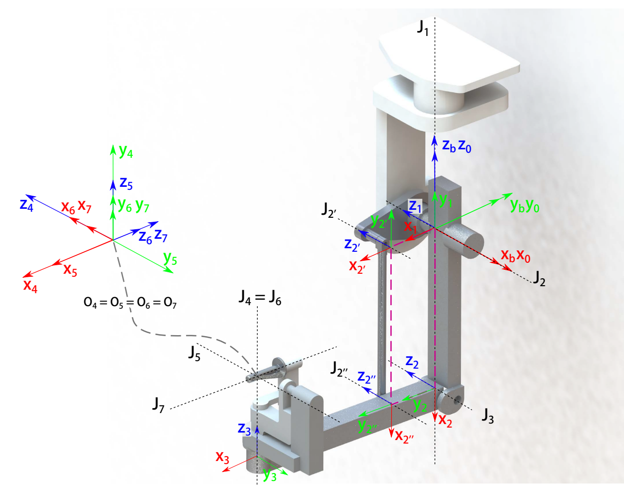

Fig. 2. Master tool Manipulator (MTM) kinematics with Denavit-Hartenberg frames

A. PSM arm

Each PSM is a 7-DOF actuated arm, which moves a surgical instrument about a Remote Center of Motion (RCM), i.e., a fixed fulcrum point that is invariant to the configuration of the PSM joints. The first 6 degrees of freedom correspond to Revolute (R) or Prismatic (P) joints, combined in a RRPRRR sequence. The last degree of freedom, corresponding to the opening and closing motion of the gripper, is not considered here. Moreover, the PSM arm is mounted on a passive base (the so-called setup joint) which allows translating and rotating the arm with respect to the patient. Hence, a suitable transformation matrix $\boldsymbol{T}_b^w$ of the base frame b with respect to the world frame w must be taking explicitly into account in computing the dynamic model of the PSM because it affects the gravity torque reflected at the joints.

The classical version of the Newton-Euler algorithm for open kinematic chains must be suitably modified to include the dynamic effects of: 1. the counterweight used to balance the motion of the instrument along the prismatic joint; 2. the links of the double parallelogram mechanism. In details, with reference to Fig. 1, representing the complete kinematic structure of the PSM, the forward and backward recursions can be applied to the open kinematic chain composed by joints $\{1, 2, 2', 2'', 3, 4, 5, 6\}$. An additional branch of the chain must be considered to take into account the counterweight. The effects of the double parallelogram can be accounted by imposing constraints to the kinematic variables and to the joint torques. For more details refer to [3]. Moreover, the counterweight, is modeled as a link which slides along a prismatic joint attached to link L_2 and linked by a tendon driven mechanism to the actuator of the prismatic joint 3. The friction coefficients reported in Eq. 2 are $\boldsymbol{F}_v = \mathrm{diag}\{F_{v1}, \dots, F_{v4}, \boldsymbol{F}_{vl}\}$, where $\boldsymbol{F}_{vl}$ is a (2×2) matrix and $\boldsymbol{F}_s = \mathrm{diag}\{F_{s1}, \dots, F_{s6}\}$. Matrix $\boldsymbol{F}_{vl}$ models the viscous friction for the last 2 joints, that are coupled by a tendon driving mechanism. Moreover, the elastic contribution in Eq. 3 $\boldsymbol{\tau}_e$ models the elastic forces acting on joints 1 and 2 that are created by the power cables, while an elastic torque, produced by a torsional spring, is present on joint 4. Finally, for the last three links, corresponding to the instrument wrist, the mass and inertia properties have been neglected and the corresponding parameters have been set to zero.

B. MTM arm

The two MTMs, used to remotely teleoperate the two PSMs and the endoscopic manipulator, are identical except for their wrists, that are mirrored. Each MTM is an 8-DOF manipulator. Only the first 7 degrees of freedom are considered in the kinematic and dynamic model described here, while the last degree of freedom is not actuated and is used to command the opening and closing of the instrument gripper. Moreover, two passive revolute joints $J_{2'}$ and $J_{2''}$ are defined to model the parallelogram mechanism.

The homogeneous transformation matrix $\boldsymbol{T}_7^b(\boldsymbol{q})$ can be computed, e.g., by considering the kinematic chain (see Fig. 2) $\{1, 2, 3, 4, 5, 6, 7\}$ and taking into account that the parallelogram mechanism imposes the following constraints to the joint variables: $q_{2'} = q_2 + q_3, \quad q_{2''} = -q_3$.

The computation of the dynamic model of the MSM arm, as well as the PSM arm, can be performed using the recursive Newton-Euler approach. The version of the algorithm for closed kinematic chains must be adopted, to take into account for the parallelogram mechanism. Also for the MTM the friction contribution $\boldsymbol{\tau}_f$ has been set as the sum of viscous and static friction, e.g. in Eq. 2 with $\boldsymbol{F}_s$ and $\boldsymbol{F}_v$ set as diagonal matrices. Moreover, an elastic term, is added in order to models the elastic torques acting on joint 1, due to the power cables, and on joints 4, 5 and 6, caused by torsional springs.

III. Identification of the dynamic parameters

In this work, the method proposed by Sousa e Cortesão [4] is adopted for the dynamic parameters identification. The method is based on a semidefinite programming reformulation of the least squares method and allow to preserve the physical consistency of the dynamic parameters. Moreover, the method has been modified by weighting the regressor matrix in order to compute a suitable normalization [3].

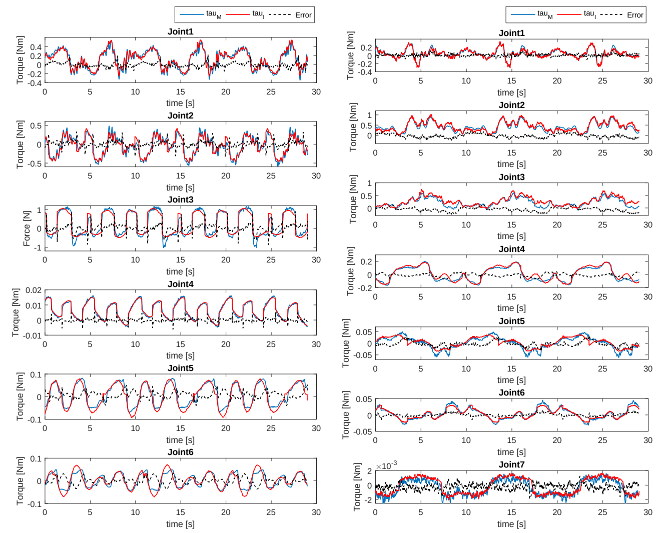

Fig. 3. Measured and computed torques along a test trajectory. Left: PSM arm, Right: MTM arm

IV. Experimental results

The identification of the dynamic parameters of both the PSM and the MTM arm is obtained using an optimal trajectory calculated to minimize the condition number of the regressor matrix, taking into account the robot kinematic constraints e.g. position and velocity joint limit [3].

Fig. 3 reports, for both the PSM and MTM arms, the measured torques and those computed using the dynamic model with the identified parameters, considering a test trajectory different from that used for the identification. The dashed line is the reconstruction error. The errors are not negligible in particular for the wrist joints of both the arms; however, the results are globally satisfactory considering the high sensors noise, especially on the joint velocities and accelerations, that are computed numerically, and the unmodelled dynamics, like friction and elasticity of the tendons.

V. Conclusion and future works

In this work the dynamic model identification of the da Vinci Research Kit robotic arms was presented. The error between the measured torques and those computed using the identified dynamic model remains below 30% for almost all the joints. Future work will be devoted to reduce this error, for example using non-linear friction models for the tendon driven joints, and to test the accuracy of the model-based sensor-less estimation of the contact forces.

References

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