A SYSTEMATIC LOAD IDENTIFICATION PROCEDURE FOR PARALLEL ROBOT MANIPULATORS

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Summary This paper presents a systematic load identification procedure for a class of parallel robot manipulators. It is considered as a regular dynamic robot identification problem since the load is rigidly fixed on the robot-platform. The challenge is that the estimation must be based only on the measurements obtained through sensors in the robot actuators. The load identification procedure is exemplified by experimental studies with a calibrated test load using periodic robot excitation.

INTRODUCTION

Advanced control techniques for robot manipulators demand the knowledge of the values of dynamic parameters of the manipulator model. At this the rigidly fixed load can be regarded as a structural modification of the manipulator. Computing such parameters on the basis of the geometry and material coefficients of the components (e.g. links, actuators) and the payload via CAD modeling techniques is inaccurate due to unmodeled dynamics and simplifications. In addition the payload geometry and material coefficients are mostly unknown in practice. Identification techniques are used in order to achieve more accurate values. In the case of serial robot manipulators, the load modifies the dynamic parameters of the last link or end effector. Due to the open kinematic chain the load parameters can be identified by a single motion of the last link. Several systematic procedures for experimental identification of serial robot manipulators exist, e.a. [2] and [4]. They estimate the parameters based on direct measurements of motion and actuator torque data during robot movements along optimized trajectories. Exploiting the simplification by a single motion of the last link is obviously not applicable to parallel robot systems with closed kinematic chains. Because the end-effector of a n-DOF parallel mechanism is connected to the base by at least n independent kinematic chains.

In this paper, we discuss a novel experimental load identification procedure for parallel robot manipulators. The estimation scheme uses the fact that the equations of motion are linear with respect to the inertia parameters and the gravity term. At first, the identification equations of the estimator are derived using the equation of motion of a rigid body written with respect to an arbitrary reference point P [1]. The experimental design is presented in the last section. We discuss a data preprocessing method, which removes the influence of the time variable Coulomb friction in the actuators, and apply a weighting matrix to compensate the unmodelled dynamics in the force measurements.

IDENTIFICATION PROCEDURE

The robot load identification procedure in this paper based on two weighted least-squares estimators. They are derived from the equations of motion of a unconstrained rigid body written with respect to an arbitrary reference point P

$$\hat{\boldsymbol{\theta}}_k = [\boldsymbol{\Phi}_k^T \boldsymbol{W}_k \boldsymbol{\Phi}_k]^{-1} \boldsymbol{\Phi}_k^T \boldsymbol{W}_k \boldsymbol{Y}_k \ , \qquad k = 1, 2 \ , \qquad \boldsymbol{Y}_k = \left[\ \boldsymbol{y}_k^T(1) \ \ \ldots \ \ \boldsymbol{y}_k^T(N) \ \right]^T \in \mathbb{R}^{3N} \tag{1}$$

with $\boldsymbol{W}_k \in \mathbb{R}^{3N \times 3N}$ as a weighting matrix, $\boldsymbol{\Phi}_1 \in \mathbb{R}^{3N \times 4}$ and $\boldsymbol{\Phi}_2 \in \mathbb{R}^{3N \times 6}$ as matrices of regressors, which contain N data samples of the actuator forces represented in an inertial reference frame R, the orientations, angular velocities and angular accelerations of the robot-platform (see Fig. 1). The unknown inertia parameters are the load mass, the center of gravity and the inertia matrix of the load. In the *first step* the estimator (1) with index $k = 1$ is used to calculate the unknown mass of the load and common center of gravity of the load and the robot platform. The parameter vector $\boldsymbol{\theta}_1$ is defined as

$$\boldsymbol{\theta}_1 = \left[\ 1/m \quad \boldsymbol{r}_{Cp}^L \ \right]^T \in \mathbb{R}^4 \ , \qquad m = m_l + m_r \ , \qquad \boldsymbol{r}_{CP}^L = \left[\ x_{CP}^L \ y_{CP}^L \ z_{CP}^L \ \right]^T \tag{2}$$

with the load mass m_l and the robot-platform mass m_r. The center of gravity $\boldsymbol{r}_{CP}^L$ with respect to the body-fixed frame L of the robot-platform refers to a reference point P, that is, in this case, located at the surface of the platform. The $3N \times 1$ column vector $\boldsymbol{Y}_k, k = 1$ in (1) consists of the translational acceleration of the platform with respect to frame R where $\boldsymbol{y}_1(i)$ is defined as

$$\boldsymbol{y}_1(i) = [\ 0 \ \ 0 \ \ g \ \ ]^T - [\ \ \ddot{x}_P^R(i) \ \ \ddot{y}_P^R(i) \ \ \ddot{z}_P^R(i) \ \ ]^T \qquad \text{for} \qquad i = 1, \ldots, N \ . \tag{3}$$

These translational accelerations are not necessarily measured directly. We exploit the Jacobian inverse solution for nonredudant parallel manipulators [3] to calculate the motion of the platform based only on standard sensors integrated in the actuators (see the following section). The matrix of the regressors $\boldsymbol{\Phi}_1$ is written as

$$\boldsymbol{\Phi}_1 = \left[\sum_{j=1}^{n_A} \boldsymbol{F}_j^R \qquad \boldsymbol{A}^{RL} \, \tilde{\boldsymbol{\omega}}_{LR}^L \, \tilde{\boldsymbol{\omega}}_{LR}^L + \boldsymbol{A}^{RL} \, \dot{\tilde{\boldsymbol{\omega}}}_{LR}^L \right] \in \mathbb{R}^{3N \times 4} \tag{4}$$

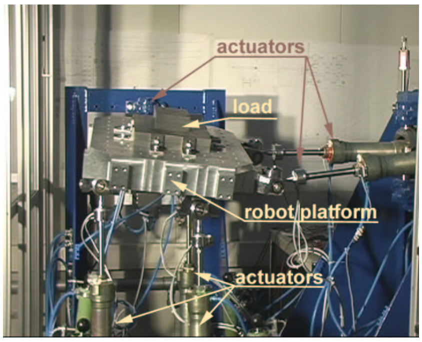

Figure 1. Experimental setup: Parallel robot manipulator powered by six pneumatic actuators with a calibrated load ($m_l = 22.26$ kg).

with $n_A = 6$ as the number of actuators of the parallel mechanism (see Fig. 1) and $\boldsymbol{A}^{RL}$ as the orientation matrix of the robot-platform with respect to an inertial frame R. The external force vector $\boldsymbol{F}_j^R,\ j = 1, \ldots, n_A$ in (4) can be calculated by the measured actuator forces and direct kinematic equations, which transform the body-fixed frame of each actuators in the inertial frame. The matrix elements of $\tilde{\boldsymbol{\omega}}_{LR}^L \in \mathbb{R}^{3\times3}$ and $\dot{\tilde{\boldsymbol{\omega}}}_{LR}^L \in \mathbb{R}^{3\times3}$ consist of the vector components of the angular velocities and angular accelerations of the robot-platform with $\boldsymbol{\omega}_{LR}^L = [p^L\ q^L\ r^L]^T$ and $\dot{\boldsymbol{\omega}}_{LR}^L = [\dot{p}^L\ \dot{q}^L\ \dot{r}^L]^T$ with respect to frame R represented in L. As before the translational accelerations in (3), the determination of this is based only on the measured actuator positions, velocities and accelerations using the Jacobian inverse solution. In the *second step* of the identification process the estimator (1) for $k = 2$ is used to calculate the unknown common inertia tensor of the robot-platform with the rigidly fixed load. Here, the parameter vector is defined as $\boldsymbol{\theta}_2 = \left[\ J_{Cx}^L\ J_{Cy}^L\ J_{Cz}^L\ J_{Cxy}^L\ J_{Cyz}^L\ J_{Cxz}^L\ \right]^T \in \mathbb{R}^6$ with three moments of inertia and three products of inertia represented in body-fixed frame. The vector $\boldsymbol{Y}_2 \in R^{3N}$ in (1) consists of the external torques, calculated by the actuator forces using the manipulator kinematic equations, the estimated mass $\hat{m}$, and the center of gravity defined by $\hat{\boldsymbol{r}}_{CP}^L$, which are estimated before. The elements of this vector and the matrix $\boldsymbol{\Phi}_2 \in \mathbb{R}^{3N\times6}$ are described in detail in [1]. The *last step* of the procedure regards the fact that the estimated parameter vectors $\boldsymbol{\theta}_1$ and $\boldsymbol{\theta}_2$, obtained from the least-squares formulation (1) using (3) and (4), are a combination of the inertial parameter of the platform *and* the load. For this, we apply the parallel axis theorems for moments and products of inertia to seperate known robot manipulator parameters (e.g. as a result of an estimation process without a load) from the desired parameters of the load.

EXPERIMENT DESIGN

The design of the identification experiment includes the planning of the robot trajectory and the choices, which measured signal should be used to obtain the regressors in (1). We use a sinusoidal trajectory to excite the three orientation angles of the robot-platform during one experiment. As mentioned before the estimation is based only on signals that are readily available through sensors integrated into the actuators. The piston positions, piston velocities, and piston accelerations of the pneumatic actuators are measured. In addition, the chamber pressure measurements $p_{I,II_j}(i)$ with $i = 1, \ldots, N$ for $j = 1, \ldots, n_A$ are recorded to calculate the actuator forces. Yet another important point is that the unmodeled robot dynamics such as friction must be compensated in the data recording. First, a goal-oriented data-preprocessing method is used to reduce the influence of the friction in the actuators using a combination of Coulomb and viscous friction models. The second scheme takes into account the influence of unmodeled stick-slip motion in low-velocity regimes caused by Stribeck friction on the calculation of the actuator forces. For this purpose the following weighting matrix in (1) is chosen: $\boldsymbol{W}_k = \text{diag}\left[w_k(\bar{v}(1)), w_k(\bar{v}(1)), w_k(\bar{v}(1)),\ \ldots, w_k(\bar{v}(N)), w_k(\bar{v}(N)), w_k(\bar{v}(N))\right] \in \mathbb{R}^{3N\times3N}$ for $k = 1, 2$ with a time-dependent average value $\bar{v}(i)$ of the measured piston velocities $v_j(i)$ for $j = 1, \ldots, n_A$ and a weighting function w_k, that goes to zero at low-velocity regimes.

CONCLUSION

In this paper a systematic load identification procedure has been presented and applied to a parallel robot manipulator using only measurements from sensors integrated in the actuators of the robot. Furthermore, it is of interest to consider the quality of a recursive weighted least-squares algorithm for the purpose of adaptive control.

References

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