Experimental identification of the static model of an industrial robot for the improvement of friction stir welding operations

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SUMMARY. Friction stir welding (FSW) is a joining process where the regulation of some technological parameters, like machining forces and tool velocities, is essential to ensure the required product quality. Therefore industrial robots are often equipped with force sensors in order to have a monitoring of the interaction forces between the rotating tool and the sheets metal. Alternatively a mathematical model can indirectly provide information about such forces through current measurements of robot motors. The present work focuses on the experimental identification of the static model of the Tricept HP1, a robot suitable for FSW operations because of its high thrust performance. Gravity and friction contributions are taken into account, while inertial terms are neglected from modeling according to the low speed motion involved in the welding process. The model is conveniently used to investigate the axial force developed during welding of aluminum sheets metal, laying the groundwork for a model-based control of the robot.

1 INTRODUCTION

Nowadays many industrial processes of sheet metal manufacturing still rely on the use of CNC machines for the stiffness and reliability they ensure, but a flexible production is often required in industry because of reduced and extremely variable batches. Serial industrial robots offer such flexibility, but large size robots are often necessary in order to provide the required stiffness. The Tricept HP1, a hybrid robot with a parallel kinematics shoulder, has been successfully used to carry out sheet metal forming [1] and friction stir welding operations on aluminum sheet metal alloys, showing its effective applicability to industrial processes where high interaction forces are needed.

However several welding tests have highlighted the complexity of the operation because of the high sensitivity of FSW process to technological parameters [2], such as the thrust of the welding tool which is instrumental in achieving a good quality of the weld. It follows the need to realize force control systems with load cells integrated at the robot end-effector for a direct feedback of the machining loads [3]. Force information can be also deduced by measuring the spindle motor power, identifying a mathematical model to be introduced in the control algorithm [4]. A more complex option is the use of the robot dynamics model [5], which needs a preliminary procedure for its experimental identification [6]. Many mathematical tools are available to investigate the identifiability of dynamics parameters [7] aimed at finding base parameters.

The present work is focused on the static modeling of the Tricept robot, providing a relation
between motor torques and the external forces the end-effector is subjected to [8]. The effect of friction and the contribution of gravitational torques are investigated and many experimental tests allowed to validate the obtained results [9-11]. Dynamics parameters can be neglected from the study because of the low planned speed of the robot motion. The static model of the robot can be used for two purposes: on the one hand, as an investigative tool for the evaluation of the machining loads required in the welding of sheets metal and, on the other hand, as an indirect measurement instrument of the external forces for the implementation in model-based control algorithms, therefore regulating FSW technological parameters during the manufacturing process.

2 KINEMATICS MODEL OF THE TRICEPT ROBOT

Tricept HP1 robot belongs to the family of Hybrid Parallel Kinematics Machines (HPKMs) because it is made up of a parallel kinematics arm and a serial roll-pitch-roll (RPR) wrist. The arm can be represented in schematic form as shown in Figure 1a: a mobile platform is connected to a fixed base by means of three identical actuated legs and a radial passive link. Each actuated leg consists of a ball screw which drives the slide of a piston inside a cylinder. All cylinders are connected to the fixed base with a universal joint at the vertices $U_i$ ($i = 1, 2, 3$) of an equilateral triangle of side $a = 600$ mm, while pistons to the mobile platform at the vertices $S_i$ of a smaller equilateral triangle of side $b = 175$ mm. The kinematics of such legs can be synthetically expressed with the acronym UPS, which commonly stands for a Universal-Prismatic-Spherical sequence of joints where the prismatic pair is actuated. Analogously, the radial link, which is rigidly connected to the moving platform, has a UP kinematics, meaning that the link is joined with the fixed frame at the center of the base triangle by means of a universal joint, while a prismatic pair allows its sliding along the radial direction.

Figure 1: Sketches of the parallel arm (a) and of the RPR serial wrist of the Tricept robot.

Kinematics and dynamics models of the Tricept robot have been already investigated by Caccavale et al [1]; some expressions are provided again in the following with necessary modifications. Two reference frames can be defined for the parallel arm: $(A; x_A, y_A, z_A)$ at the center of the fixed base and $(B; x_B, y_B, z_B)$ at the center of the moving platform. The position of the vertexes $U_i$ and $S_i$ can be expressed respectively to points $A$ and $B$ by means of $\varphi_i$ angles ($0^\circ, 120^\circ, 240^\circ$), which give the direction of vectors $a_i = (U_i - A)$ and $b_i = (S_i - B)$ in the platforms.
plane with respect to unit vectors \( x_A \) and \( x_B \). The position vector \( r = (B - A) \) can be expressed in polar coordinates \( q_A = [r, \alpha, \beta]^T \), where a rotation \( \alpha \) occurs around the fixed unit vector \( y_A \) and a negative rotation \( \beta \) around a mobile unit vector aligned with \( x_B \), whose direction cosines are \([\cos(\alpha), 0, -\sin(\alpha)]^T \) in the fixed frame. \( R_Y(\alpha), R_X(-\beta) \) are their respective conventional rotation matrices.

Inverse kinematics equations of the parallel arm, resulting from the application of the loop closure equation between points \( A, U_i, S_i, B \) of each leg \((i=1,2,3)\), point out geometric parameters and variables entailed into the mathematical model:

\[
\begin{align*}
  d_1 &= (A + r' + Dc\alpha - Es\cos\beta + Fc\beta + Grs\cos\beta - Hrs\beta)Y \\
  d_2 &= (A + r' + Bc\alpha + Crs\cos\beta)Y \\
  d_3 &= (A + r' + Dc\alpha + Es\cos\beta + Fc\beta + Grs\cos\beta + Hrs\beta)Y
\end{align*}
\]

with

\[
\begin{align*}
  A &= \frac{a^2 + b^2}{3} \\
  B &= -\frac{2}{3}ab \\
  C &= -\frac{2}{\sqrt{3}}a \\
  D &= -\frac{ab}{6} \\
  E &= -\frac{ab}{2\sqrt{3}} \\
  F &= \frac{ab}{2} \\
  G &= \frac{a}{\sqrt{3}} \\
  H &= -a \\
  sa &= \sin(\alpha) \\
  ca &= \cos(\alpha) \\
  sb &= \sin(\beta) \\
  cb &= \cos(\beta)
\end{align*}
\]

Equations (1) provide an explicit relation between the vector \( q_A \) of polar coordinates and the vector \( d_A = [d_1, d_2, d_3]^T \) of the displacements of the actuated prismatic joints, which gather the distances \(|S_i - U_i|\) between spherical and universal joints of each leg. On the contrary the direct kinematics problem of the parallel arm needs a numerical algorithm, for instance based on Newton-Raphson method, to find out the roots of a system of implicit equations.

A sketch of the serial wrist is shown in Figure 1b: the position and the orientation of a reference frame \((C; x_C, y_C, z_C)\) at the end-effector can be related to the position of frame \((B; x_B, y_B, z_B)\) once defined the conventional rotation matrices \( R_Z(\theta_1), R_Y(\theta_2), R_Z(\theta_3) \). Wrist rotation angles are gathered in the wrist joint vector \( q_W = [\theta_1, \theta_2, \theta_3]^T \). Point \( E \) is defined at the center of the spherical wrist and it is located at a fixed distance \( l = 282 \) mm from point \( B \) and \( h = 155 \) mm from \( C \).

The orientation of reference frame \((C; x_C, y_C, z_C)\) with respect to \((A; x_A, y_A, z_A)\) can be obtained combining the mentioned rotation matrices as follows:

\[
^{A}R = R_z(\alpha)R_y(-\beta)R_z(\theta_1)R_y(\theta_2)R_z(\theta_3)
\]

The rotation matrix on the left of (2) can be defined in terms of Euler angles \((\phi, \theta, \psi)\) with the ZYZ convention, even implemented by the robot controller to drive end-effector orientations. Equation (2), together with the following equation (3), can be used to complete the direct kinematics of the whole robot if Euler angles are explicitly evaluated. Moreover, unit vectors \( z_B \) and \( z_C \), needed for the computation of position vector \( p_{EE} = (C - A) \) can be derived from matrices entailed in (2):
The global Jacobian matrix $\mathbf{J}$ of the Tricept robot between end-effector and joint velocities derives from equations (1)-(3) after computations of time derivatives. It follows

$$
\begin{bmatrix}
\dot{p}_{EE} \\
\omega_{EE}
\end{bmatrix} =
\begin{bmatrix}
J_{pa} & J_{sw}
\end{bmatrix}
\begin{bmatrix}
d \\
q
\end{bmatrix}
= \mathbf{J}
\begin{bmatrix}
d \\
q
\end{bmatrix}
$$

(4)

where the Jacobian sub-matrices are related to Linear and Angular velocities of the end-effector for their Arm and Wrist joints contribution. Matrix $\mathbf{J}_{pa}$ is the Jacobian of the Parallel Arm obtained from time derivatives of equation (1).

3 STATICS MODEL OF THE TRICEPT ROBOT

Model-based control algorithms are generally referred to control systems based on the dynamics model of a robot, making reference to all the inertial, gravitational and friction terms. In the present work the attention is focused on a statics model, where only gravity and friction effects are taken into account. Such assumption is plausible when the robot is moved at constant and slow speed, for example in a wide range of robotized friction stir welding or incremental forming applications. Such operations involve also external forces and moments, which have to be modeled. Therefore the statics of the Tricept robot is presented in the form:

$$
\mathbf{\tau} = \mathbf{\tau}_g + \mathbf{\tau}_f + \mathbf{J}^T \mathbf{F}
$$

(5)

where $\mathbf{\tau}_g$ is the torque gravity vector, $\mathbf{\tau}_f$ is the torque vector of static and dynamic friction, $\mathbf{J}$ is the Jacobian matrix presented in (4) and $\mathbf{F}$ is the vector of external generalized forces. Vector $\mathbf{\tau}$ on the left member of (5) is the vector of generalized torques at the joints: it is made of the forces which actuate the prismatic joints of the parallel arm and the torques which drive the revolute joints of the serial wrist. Torques at the motor axes can be obtained once given the speed ratios of the transmissions.

Under the mentioned assumptions, it is useful to derive the expression of the gravity vector and to estimate the friction contribution to motor torques. Lagrange's equation is reduced to the derivative of the potential energy, given by all the robot members, with respect to generalized coordinates $\mathbf{q} = [d_1, d_2, d_3, \theta_1, \theta_2, \theta_3]^T$. Mass and geometric parameters which are involved in the formulation are collected in Table 1: approximate values have been estimated from CAD modeling, according to the technical data reported in the robot manual about the total mass and the center of
mass of the whole robot.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pistons</td>
<td>( m_p, l_p )</td>
</tr>
<tr>
<td>cylinders</td>
<td>( m_c, l_c )</td>
</tr>
<tr>
<td>radial link</td>
<td>( m_r, l_r )</td>
</tr>
<tr>
<td>wrist link</td>
<td>( m_w, l_w )</td>
</tr>
</tbody>
</table>

Table 1: Estimated mass and geometric parameters of the Tricept robot.

Figure 2 highlights the meaning of the parameters, where \( m \) and \( l \) are constant values representing the mass and the position of the center of mass of all the members.

Figure 2: Masses and centers of mass positions.

As shown in Figure 3 the work cell is realized with the robot arranged in a horizontal configuration with its end-effector facing a stiff vertical plate, where the object is tightened before machining operations. It follows that the gravity vector acts along the \( x_A \) axis of the fixed frame, with \( \mathbf{g} = [g, 0, 0]^T \). Moreover a spindle with an angular speed reducer is connected to the robot terminal flange, contributing to the statics model with a further mass \( m_t \) and the position vector of its centre of mass, whose components are \( l_{tx} \) and \( l_{tz} \) with respect to point \( E \) with the orientation of system \( (C; x_C, y_C, z_C) \).
The torque gravity vector of (5) can be arranged in linear form collecting all the eight parameters $m_i$ and $m_i l_i$ obtained from Table 1. However a study of the rank of the observation matrix, also called regressor matrix, for different configurations of the robot, revealed a number of base parameters reduced to 5, namely the rank value. After an analysis of such matrix the following base parameters can be obtained and gathered in vector $\pi_{id}$

$$\pi_{id} = \begin{bmatrix} 3m_r + m_s + m_a & m_1 l_1 + m_2 l_2 & m_1 l_1 - m_2 l_2 & m_1 l_1 + m_2 l_2 & m_1 l_1 \end{bmatrix}^T$$ (6)

Therefore the torque gravity vector modifies by introducing the $6 \times 5$ observation matrix $Y_{id}(q)$, obtained gathering the coefficients of the elements in (6):

$$\tau = Y_{id}(q) \pi_{id}$$ (7)

Matrix $Y_{id}(q)$ can be easily inverted to solve for the defined base parameters, but motor torques are strongly affected by friction, which must be introduced in the static model. Only Coulomb contribution is considered because of the low speed motion of the robot during friction welding according to the following formulation:

$$\tau_f = D(q) \pi_f$$ (8)

where $D$ is a $6 \times 12$ matrix depending on the actuated joint velocities and vector $\pi_f$ gathers the 12 constant and positive friction coefficients $f_{C,q_i}$. The first six columns of $D$ are related to Coulomb coefficients for positive motion of the actuated joints, while the second for negative motion, having introduced a different behavior associated to the direction of each joint displacement. The square sub-matrices of $D$ are diagonal and depend on the sign of joint velocities.

Eventually, vectors $\pi_{id}$ and $\pi_f$ are collected in a single vector $\pi$ of $n_b=17$ base parameters and the overall observation matrix changes accordingly.

4 EXPERIMENTAL IDENTIFICATION OF BASE PARAMETERS

The proposed static model refers to low speed applications of the robot, where forces at the robot-environment interface produce significant motor torques if compared with gravity and friction terms, according to equation (5). While external forces are related to motor torques by
means of the transposed Jacobian matrix, which is assumed to be known with sufficient accuracy, the other terms are unknown and should be identified, in particular friction torques, for which a reference value cannot be available.

The aim of the work is to find a structural model, namely a minimum set of physical parameters: several measures of motor torques during a planned motion of the robot are needed to carry out the identification procedure. Four joint configurations, covering a large part of the robot workspace, have been defined as motion targets, ensuring that all the motors would be excited by gravity loads and that they would move in both positive and negative directions. A measure of motor currents, and the corresponding actual positions of the joint axes, allows to have a feedback of the motor torques once given the motor torques constants. $N$ measurements of the motor torques along the planned joint trajectories, at the serial communication frequency of 6 Hz, are collected in the conventional form:

\[
\begin{bmatrix}
\tau_1 \\
\vdots \\
\tau_s
\end{bmatrix} = \begin{bmatrix}
Y_d(q_1) & D(q_1) \\
\vdots & \vdots \\
Y_d(q_s) & D(q_s)
\end{bmatrix} \begin{bmatrix}
\pi_{id} \\
\pi_f
\end{bmatrix} = Y(q,q)\pi
\]

(9)

If the $6N \times nb$ matrix $Y$ has full rank, in this case 17, then equation (9) can be inverted to find the $\pi_{es}$ estimated parameters by ordinary least squares:

\[
\pi_{es} = (Y^TY)^{-1}Y^T\tau_m = Y^T\tau_m
\]

(10)

where $Y^T$ is the pseudo-inverse matrix of $Y$ and $\tau_m$ is the $6N$-dimension vector of measured motor torques. Estimated mass and geometric parameters of table 1 can be conveniently exploited to address the least square optimization procedure incorporating them in the static model [12]. After a scaling procedure applied to the base parameters vector which combines different units terms, unlike vector $\tau$ which is homogeneous, the base parameters of vector $\pi_{es}$ derive from the application of equation (10). Their identified values, compared with the initial CAD estimates, are shown in table 2.

<table>
<thead>
<tr>
<th>$\pi_{id}$</th>
<th>Initial estimate</th>
<th>145.0 kg</th>
<th>9.0 kgm</th>
<th>40.4 kgm</th>
<th>6.0 kgm</th>
<th>2.1 kgm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identified parameters</td>
<td>147.7 kg</td>
<td>8.2 kgm</td>
<td>39.2 kgm</td>
<td>5.6 kgm</td>
<td>2.2 kgm</td>
<td></td>
</tr>
<tr>
<td>$\pi_{f,1-6}$</td>
<td>Initial estimate</td>
<td>0 Nm</td>
<td>0 Nm</td>
<td>0 Nm</td>
<td>0 Nm</td>
<td>0 Nm</td>
</tr>
<tr>
<td>Identified parameters</td>
<td>1.69 Nm</td>
<td>1.58 Nm</td>
<td>0.93 Nm</td>
<td>0.31 Nm</td>
<td>0.23 Nm</td>
<td>0.14 Nm</td>
</tr>
<tr>
<td>$\pi_{f,7-12}$</td>
<td>Initial estimate</td>
<td>0 Nm</td>
<td>0 Nm</td>
<td>0 Nm</td>
<td>0 Nm</td>
<td>0 Nm</td>
</tr>
<tr>
<td>Identified parameters</td>
<td>1.69 Nm</td>
<td>1.53 Nm</td>
<td>1.05 Nm</td>
<td>0.29 Nm</td>
<td>0.25 Nm</td>
<td>0.14 Nm</td>
</tr>
</tbody>
</table>

Table 2: Initial estimate and identified base parameters.
Figures 4 and 5 show the trajectories of the actuated joints together with the corresponding motor torques measured during their execution and the torques obtained with the identified $\pi_{es}$ vector, respectively for the parallel arm and the serial wrist motors. Torque steps are attributable to Coulomb friction, in fact they correspond to the change of direction of the joints movement. In the mentioned figures small time intervals during such phases of reversal of motion, where joints velocity vanishes, have been removed from the identification procedure. Moreover it can be noted that friction has a meaningful contribution to the overall motor torques and comparable with the gravitational rate.

![Parallel arm - Joint space trajectories](image1.png) ![Parallel arm - Motor torques](image2.png)

(a) (b)

Figure 4: Joint space trajectories (a) and estimated and measured torques (b) of the parallel arm.

![Spherical wrist - Joint space trajectories](image3.png) ![Spherical wrist - Motor torques](image4.png)

(a) (b)

Figure 5: Joint space trajectories (a) and estimated and measured torques (b) of the spherical wrist.

5 APPLICATION OF THE STATIC MODEL IN FSW

Experimental tests on the presented robotic cell for friction stir welding operations are carried out in order to find the axial force developed during welding. In fact, axial force is primarily responsible for the quality of the welding, together with the angular velocity of the rotating tool put in pressure against the sheets metal along the welding path. The latter is a vertical line where the sheets metal have to be joined. The robot acts along its preferential radial direction, pushing
the tool against the sheets metal surface. The material used for the tests is the aluminum alloy AA5754, provided in the form of sheets of thickness 2.5 mm. After the transient phase of pin insertion into the sheets, which is characterized by high vibrations, a stable phase of welding can be analyzed. Figure 6 shows the axial force exerted by the robot during such phase. Axial force oscillations result from using the static model of (9) in the conversion of the measured motors currents into end-effector forces. A force range of 2000-3000 N is obtained after a smoothing of the signal for an angular velocity of 2000 rpm of the tool and a welding velocity of 30 mm/min, taking into account that high frequency changes of motor currents won’t be really turned in torque at the joint axes.

Figure 6: Axial force exerted by the Tricept robot during a friction stir welding operation.

6 CONCLUSIONS

A static model of the Tricept HP1 robot is presented. Friction and gravity effects are modeled and external forces at the robot interface are related to motor torques by means of the robot Jacobian matrix. The model is identified by means of ordinary least squares after a collection of several motor currents measurements. A priori estimates of mass and geometry parameters are introduced in the identification procedure with the aim of better evaluating their real values and finding out Coulomb friction coefficients at the robot joints. Experimental tests show a strong contribution of friction with respect to gravity torques.

Finally the identified model is used to evaluate the axial force exerted by the robot during a friction stir welding operation of aluminum sheets metal. The model can be used in model-based control algorithms, for example for an impedance control where the velocity of welding and the machining axial force are monitored and controlled. Moreover, the proposed static model can be used to calibrate a further mathematical model, based on the power of the spindle in terms of current and angular velocity. The spindle current and velocity measures can be communicated to an external control board with high frequency for their processing, allowing eventually a real-time implementation in the robot controller.
References


