Articulated industrial robots: An approach to thermal compensation based on joint power consumption

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Abstract

This work focuses on the modelling, measurement and identification of the change of the kinematic chain of serial articulated industrial robots based on thermo-mechanical deformations due to self-heating. The Denavit Hartenberg convention is used to describe the kinematics of the manipulator, but the link lengths and the joint offsets are functions dependent on the motor power of the actuated neighbouring joints. These functions are measured for the Denavit Hartenberg parameters using kinematic calibration with the circle point method and identified using a linear least-squares mapping. This set of Denavit Hartenberg parameters coupled to motor power of the joints can be used to control industrial robots with a known and repeatable task program under a stable environmental temperature; as under these conditions, the thermo-mechanical deformations are mainly due to self-heating and the heat field can be assumed constant due to the repeatable task. Thus, the measurements are conducted in under a stable environmental temperature as well as in a thermal steady state with a constant heat field due to self-heating, at a given reference power. The root mean square of the measured, the interpolated and the nominal Denavit Hartenberg parameters are compared to present an estimate on the change in positioning accuracy. A case-study comprises an ABB IRB 1600, a Leica AT960 laser tracker and a FLIR SC640 infrared heat camera. The article concludes with a discussion on the opportunities and limitations of the application of the introduced thermal compensation model on articulated industrial robots and which robotic application areas could benefit from the model.

1 Introduction

Articulated industrial robots [1] have become an indispensable element of modern industrial automation solutions, as they can execute various applications while providing modern manufacturing environments with the flexibility to adapt to change.

Articulated industrial robots are significantly more repeatable than accurate [2]. Thus, users need to combine on-line and off-line programming to create task programmes. On-line programming, though accuracy independent, forces robots into undesired downtime and yield only limited transferable task programmes. On the other hand, off-line programming which reduces undesired downtimes is accuracy dependent. Hence, robot manufacturers offer calibration services to increase the accuracy and facilitate off-line programming solution. Namely, ABB offers *Absolute Accuracy* [3], KUKA offers robots with High Accuracy (HA) and FANUC offers *iRCalibration Signature* [4]. Based on the descriptions, these services use some version of kinematic calibration as described by Mooring et al. in 1991 [5]. The result is a kinematic model which accounts for the imperfect geometries and dimensions of the links as well as the configurations of the joints using a set of constant actual Denavit Hartenberg (DH) kinematic parameters. In 2013, Nubiola validated the potential accuracy improvement of a kinematic calibration [6]. However, there are also non-kinematic sources for inaccuracies such as; thermo-mechanical errors which can change the kinematic chain and or its compliance due to a change of the heat field of its structural members [7]. Thus, the thermo-mechanical errors change the kinematic DH parameters. In 1997, Heisel presented a thermal compensation strategy based on laser tracker measurements and kinematic parameters being linked to the temperature change [8]. In 2006, Poonyapak experimentally linked the change of the kinematic parameters to the rotational velocities of the manipulator [9]. In 2009, Santolaria presented an experimental approach to express the kinematics of an articulated arm coordinate measuring machines as functions dependent on temperature [10]. More recently, others such as Yin [11] and Li [12] presented other approaches to quantify the change of the kinematic chain due to thermo-mechanical errors.

This work presents an approach to express DH parameters as a function dependent on the theoretical motor power for neighbouring joints using experimental data for a set of four reference operational powers and a linear least-squares mapping for the interpolation. This approach is limited to robots in repeatable tasks and under a stable environmental temperature.

2 Modelling

The kinematics of serial chain manipulators can be modelled using homogenous transformation matrices and the DH convention, for a minimal representation of the manipulators configuration [13]. The position and orientation of link i, or rather the coordinate system attached to it, in the base coordinate system can be calculated using:

$$^{i-1}\ T_n = \prod_{i=1}^{n} {}^{i-1}\,T(a_i, \alpha_i, \theta_i, d_i)_i \qquad (1)$$

For more detailed information see [13]. The DH parameters link length a_i, link twist α_i, joint angle θ_i and joint offset d_i are sufficient to parameterize the serial kinematic chain. The nominal DH parameters for joints 1.-4. of the ABB IRB 1600 can be seen in Table 1. A conventional kinematic calibration usually identifies these parameters for specified environmental conditions of $20 \pm 2\ °C$ and an unknown temperature on the shell of the manipulator due to its operational conditions [14].

Table 1: Nominal DH parameters of the ABB IRB 1600 for joint 1.-4. The parameters for joints 5. and 6. Are excluded as these joints were not part of the calibration procedure.

$Joint$	$a_i\ [mm]$	$\alpha_i[rad]$	$\theta_i[rad]$	$d_i[mm]$
1	*0*	*0*	θ_1	*486.5*
2	*150*	$\frac{-\pi}{2}$	$\theta_2 - \frac{\pi}{2}$	*0*
3	*700*	*0*	θ_3	*0*
4	*0*	$\frac{-\pi}{2}$	θ_4	*600*

This constant set of parameters is true for an invariant temperature. But a manipulator is subjected to temperature changes from its environment and from self-heating due to the task programs. For some industrial production facilities these temperature variations can be reduced to the self-heating of the robot, as the environmental temperature is stable in a range of $\pm 2\ °C$ and the manipulators conduct a repeatable task, implying a stable heat field across its kinematic chain. When these conditions are fulfilled, one can calculate a set of DH parameters for a given task program knowing the required power at the joints P_{J_n} as the product of the actuated joint rate $\dot{\theta}_n$ and the torque at the joint τ_n:

$$P_{J_n} = \tau_n \cdot \dot{\theta}_n \qquad (2)$$

As the change of the kinematic structure is due to the amount of heat that is created in the motors at the axes of the robot, as a result of the transformation of electrical to mechanical power.

For manipulators under these conditions, the heat field generated from the task will converge to steady state conditions after at most two days for very big robots, Fanuc M-2000iA. But usually this will happen much faster, e.g. for small robots one can assume a period of a few hours.

This, for robots in repeated tasks and under invariant environmental conditions each DH parameter p_i can be expressed as a function of the motor power of an individual joint P_{J_n} adjacent to the structural member:

$$p_i\left(P_{J_n}\right) = p_{i,ref} + \Delta p_i(P_{J_n}) \qquad (3)$$

Where the parameters reference length at $p_{i,ref}$ and the change as a function of power can be $\Delta p_i(P_{J_n})$ identified using a linear least-square mapping of a set of measurement data $\Delta p_i\left(P_{J_n}\right)_{meas}$ emulating the described environmental and operational conditions:

$$\left\| \Delta p_i\left(P_{J_n}\right) \cdot P_{J_n} - \Delta p_i\left(P_{J_n}\right)_{meas} \right\|_2^2 \qquad (4)$$

This work does not couple the kinematic DH parameters and the joint motor power arbitrarily. Each DH parameter is expressed as a function of the power of the neighbouring joints, i.e. the parameters a_2, d_4 and a_3 are dependent on P_{J_2}. The coupling for this investigation can be seen in Table 2. This coupling has been selected due to the placement of the motors according to Figure 1.

Table 2: Coupling of the DH parameters to the power of the motors at joints.

	P_{J1}	P_{J_2}	P_{J_3}
a_2	$a_2(P_{J1})$	$a_2(P_{J_2})$	$-$
d_4	$d_4(P_{J_1})$	$d_4(P_{J_2})$	$d_4(P_{J_3})$
a_3	$-$	$a_3(P_{J_2})$	$a_3(P_{J_3})$

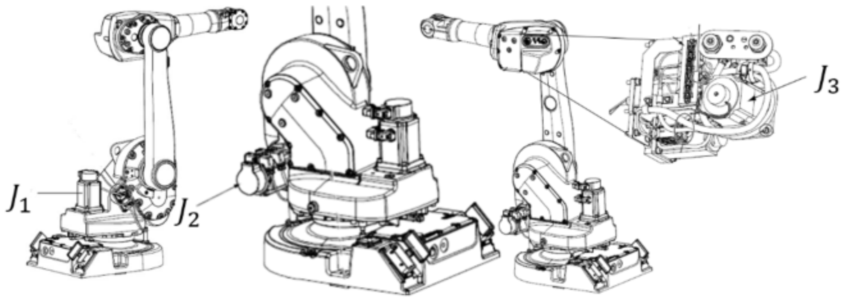


Figure 1: Motor placement of the ABB IRB 1600 [15]

3 Measurement

The measurement setup can be seen in Figure 2. The setup comprises an ABB IRB 1600 which has a payload of 10 kg and a range of 1450 mm (1), an adapter from the manipulator’s mechanical interface to the SMR nest (2), an SMR nest (3) for a 1.5" SMR, a Red-Ring Reflector (RRR) 1.5" (4) a Leica AT960 (5) [16] and a FLIR SC640 infrared camera (6).

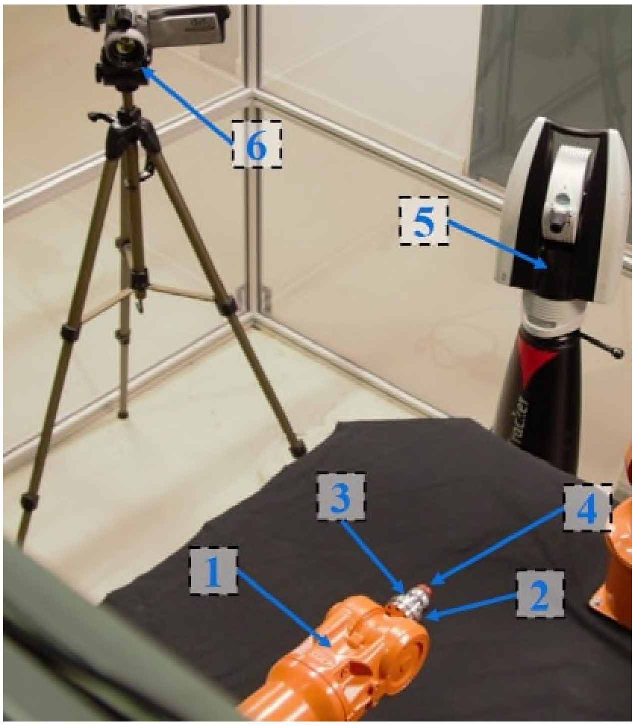


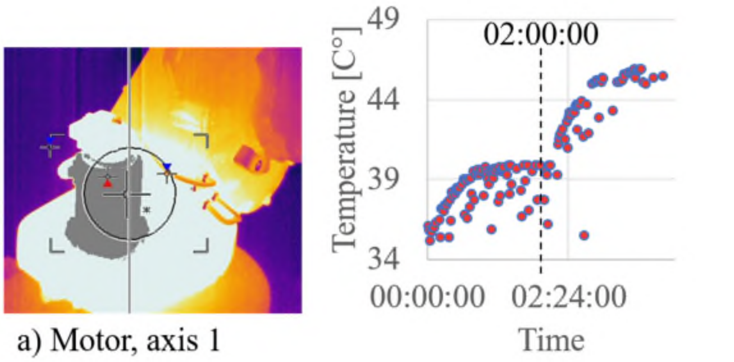
Figure 2: Measurement setup

The measurements have been performed over 24 hours using the continuous measurement function of the laser tracker together with the circle point method for the analytic identification of the DH parameters. This means that the model parameters have been identified explicitly. For joints 1-3 four different power levels have been measured: $P_{J1} = [22, 60, 115, 126]$, $P_{J2} = [18, 52, 94, 112]$ and $P_{J3} = [9, 20, 35, 38]$. This corresponds to fixed velocities of 300 (10%), 750 (25%), 1200 (40%) and 1350 (45%) mm/sec a. Ideally, the measurements should have been conducted at speeds of 25%, 50% and 75% and 100% of the maximum velocity. As these values would have covered the whole operational power range. This was not possible due to the space constraint on the relative placement of laser tracker to robot and the rotational speed of the measurement head of the AT960.

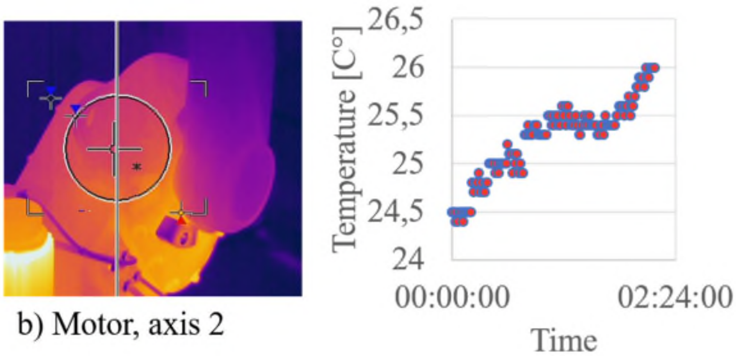
Each of the three joints has been manipulated individually and continuously, using automatic mode [1], for two hours at each power level. This number of repetitions ensured that the heat field of the manipulator converged. Namely, for joint 1.: 1224 reps. at $P_{J1} = 22$, 2912 reps. at $P_{J1} = 60$, 3703 reps. at $P_{J1} = 115$ and 4838 at $P_{J1} = 126$. The number of repetitions increased roughly by a factor of 3 for joints 2. and 3. due to the decreased length of the trajectory.

After two hours, five repeated kinematic calibrations for joints 1, 2, 3 and 5 were measured using the circle point method at an EE Cartesian velocity of 100 mm/sec. For the circle point method, the following ranges were covered: joint 1

[-30,30], joint 2 [-20, 0], joint 3 [-30, 0] and joint 5 [-20, 20]. Then the same procedure was repeated at the next higher power level. Then the same procedure was repeated for the next joint, i.e. start: hour 00:00, joint 1, $P_{J1} = 22$; end: hour 24:00, joint 3, $P_{J1} = 38$.
Due to the selected setup d_6 cannot be identified as the RRR is mounted in the centre of the manipulator's mechanical interface and d_1 cannot be identified due to the circle point method was not possible to identify the rotational DH parameters.
The measurement needed to ensure that the modelling preconditions, stable environmental temperature and heat field, are applicable. For that the environmental temperature has been measured using the weather station of the AT960. The environmental temperature has been maintained between 16.7°C and 18.9°C. The FLIR SC640 infrared camera was used to confirm that the heat field had converged. In addition to that, a Fluke 561 infrared thermometer was used each 8 hours to readjust for the actual reflected temperature of the measured object and adjust the difference to less than 1°C. Continuous measurements were taken in three different spots close to the motors in axes 1, 2 and 3. The results can be seen in Figure 3. Each motor at axes 1, 2 and 3 have been measured for 8 hours. Unfortunately, not all measurement data were recorded successfully. There are 4 hours for motor axis 1, 2 hours for motor axis 2 and 6 hours for motor axis 3.



a) Motor, axis 1



b) Motor, axis 2

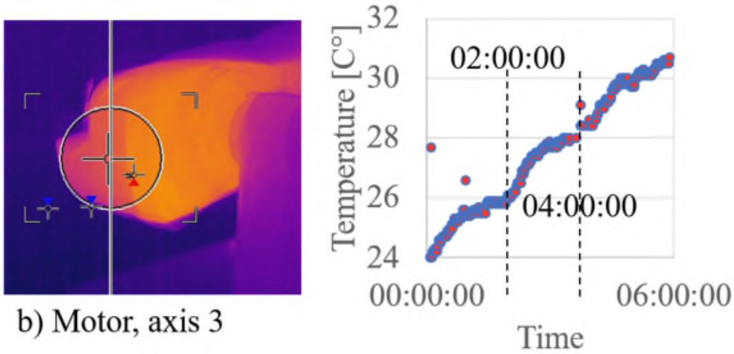


Figure 3: Measurement of the manipulator taken with the infrared camera at positions close to the motors at a) axis 1 b) axis 2 and c) axis 3

The measured temperature at the spots converged to a stable temperature after 2 hours, independent of the motor axis. This is probably not true for the whole heat field, which puts a further limitation on the applied measurement. However, this limitation could be overcome by measuring for a longer time.

4 Results

The translational DH parameters a_2, d_4 and a_3 have been identified form the measurement data using the linear least-squares mapping described in Equation (4). The nominal, the measured and the fit of the parameters as a function dependent on (P_{J_2}) can be seen in Figure 4. The Root Mean Square (RMS) value for $a_2(P_{J_2})$ is $RMS(\,a_2(P_{J_2})) = 0.02\;mm$ compared with $RMS(a_2) = 0.09\;mm$, compared to the measurement data. Respectively for $d_4(P_{J_2})$ the values are $RMS(\,d_4(P_{J_2})) = 0.025\;mm$ and $RMS(d_4) = 0.1\;mm$ and $a_3(P_{J_2})$ are $RMS(\,a_3(P_{J_2})) = 0.02\;mm$ and $RMS(a_3) = 0.055\;mm$. Hence, the difference between the nominal and the actual DH parameter can be significantly reduced for manipulators in repeatable tasks, with a stable heat field, and stable environmental conditions by conducting a kinematic calibration which links the change of the parameter to the power required for the task program.

The proposed measurement method is unable to identify all DH parameters. As mentioned earlier, due to the selected setup the DH parameters d_1 and d_6 cannot be identified.

Additionally, bigger actuated joint domains would have been preferable for the circle point method. This was not possible due to the rigid mount of the RRR which maintains the RRR position also at higher speeds. This constraint with the requirement to have an $R^2 < 0.01$ mm for the fitting of the circles, has led to the application of a sphere fit instead of a circle fit. Thus, it was not possible to identify the angular DH parameters.

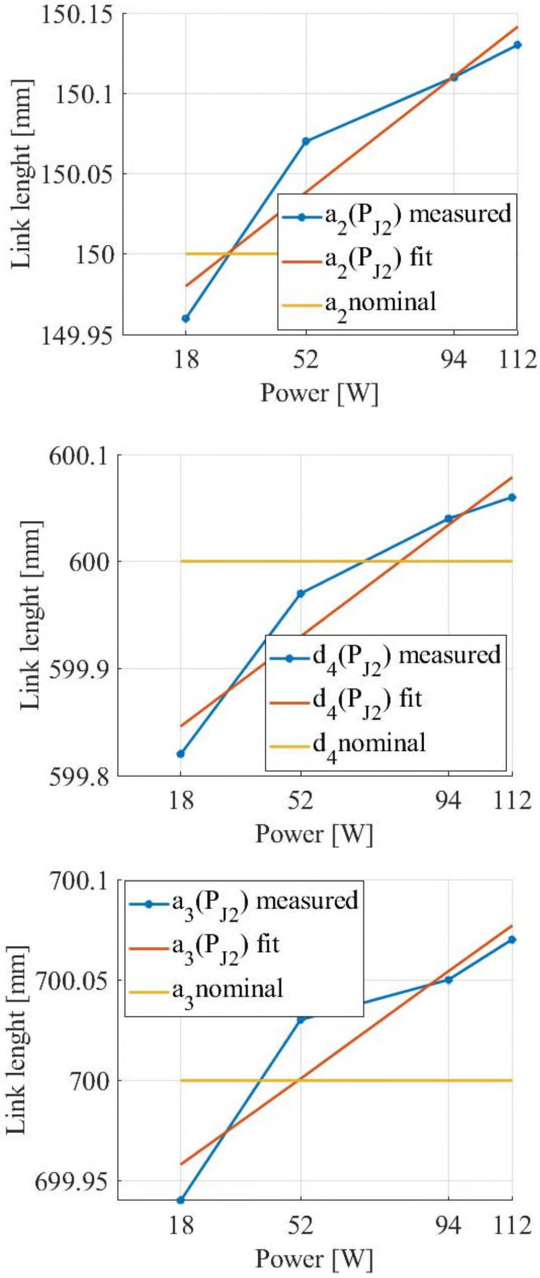


Figure 4: Plot of the measured, interpolated and nominal parameters $a_2(P_{J_2})$, $d_4(P_{J_2})$ and $a_3(P_{J_2})$.

5 Conclusions

This work has presented a novel approach to experimentally express the kinematic parameters of serial articulated manipulators as a function of the power consumption of individual joints. This model-based approach is applicable for manipulators that operate under stable environmental conditions and have repetitive task programs, as for these manipulators the thermo-mechanical related changes of the kinematic parameters can be traced to the power required by each joint motor. Typical industrial environments which fulfil these conditions are the automotive industry as well as consumer electronics.

The results of a case study, which has been conducted on an ABB IRB 1600, using laser tracker measurements, an IR camera, warm-up cycles and the circle point method for the identification of the parameters, has been presented. For three selected parameters it has been shown the root mean square error for DH parameters dependent on the linear least-square fit is significantly less than using the nominal parameter compared to the measured set of parameters. This is promising, as this means that the proposed calibration procedure potentially yields a higher utility value than a standard kinematic calibration; while it does not require additional resources, but one, more measurement time.

However, the presented calibration procedure seems only applicable in cases in which a kinematic calibration is conducted anyhow, but it could serve those, who require an increased level of accuracy even compared to the conventional kinematic calibration. Robot manufacturers could expand their services to companies in the automotive and aeronautical sectors, as these usually fulfil the requirements of stable environmental conditions and repeated tasks.

Nevertheless, the proposed method, just as any other non-kinematic manipulator calibration, suffers from the lack of opportunities to implement the identified parameters into the robot controllers.

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