

# AN END TO END SOLUTION FOR ROBOTIC WORKCELL CALIBRATION AND PERFORMANCES ASSESSMENT

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## ABSTRACT

*This paper describes an integrated approach, including performance assessment, calibration and task parameter updating, for robot calibration technology as a support to predictable, reliable and safe autonomous robotics operations in space.*

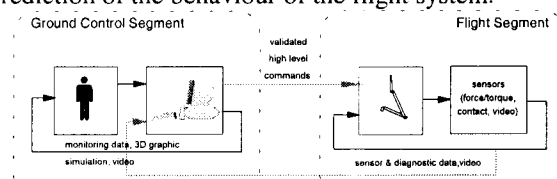
*The paper will discuss (1) performance assessment, i.e. to characterise a system via a well defined set of standardised engineering values (ANSI-RIA, ISO), and (2) calibration, i.e. system modelling and computing the model parameters, of both the environment (called workcell calibration) and the robotics device. Both will make use of hardware and software tailored for either on-ground or in-orbit use as the available resources are quite different.*

*The paper will also describe the developed H/W and S/W tools which support the calibration technology implementation. The results of the calibration are finally fed back to the pre-programming via an update of the model of the system in the off-line programming system.*

## 1. BACKGROUND

In order to be able to operate Automation and Robotics (A&R) devices in a predictable, safe and cost efficient way, the use of off-line programming techniques is preferred for the mission preparation. In addition, significant communication delays are often an important constraint for motion execution via a closed loop control over the ground segment. Therefore, the European Space Agency (ESA) has been defining the Interactive Autonomy mode of operation, see figure 1, to make the flight segment control loop independent from the communication delay. The interactive mode of

operations consists of a high rate positioning feedback loop closed at the flight segment and a low rate position commanding loop over the ground segment. This mode of operation is insensitive to communication delays, but it relies on an accurate knowledge of the kinematics and dynamics of the A&R devices to guarantee a successful execution. The commanding is based on pre-programming and optimisation of the motion based on a prediction of the behaviour of the flight system.



**Figure 1: Control loops Interactive Autonomy**

As a result effort has been spent in the last few years on robot calibration technology to set-up an integrated approach aiming at modelling A&R devices and determining the model parameters via on-ground and in-orbit performance assessment and on-ground and in-orbit calibration [1,2,3].

## 2. PERFORMANCE ASSESSMENT

Performance assessment aims at characterising a system via a well defined set of standardised engineering values computed from a standardised measurement set. These values are given by norms such as ANSI-RIA and ISO9283 and additional values are added for application dependent purposes or on the basis of industrial experience. A short list of engineering values is pose accuracy and repeatability, path accuracy and repeatability, cornering overshoot and round-off errors, hysteresis, minimum positioning time (arm oscillations), etc.

To summarise the performance assessment:

- quantifies the system performance characteristics;
- enables to determine whether the requirements for an operation can be met with the chosen system;
- and indicates the need for calibration.

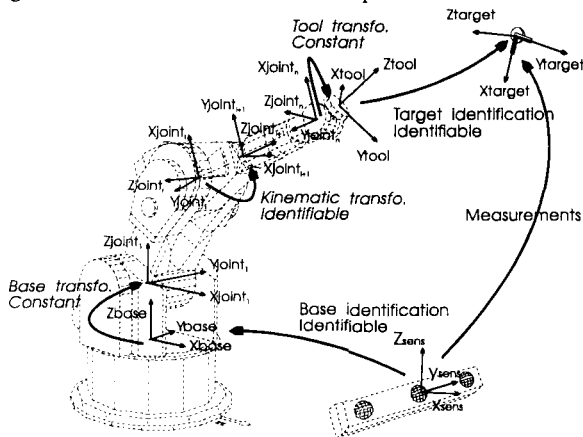
### 3. CALIBRATION

"Calibration" is the whole process which aims at improving the knowledge of the system; it involves modelling, measuring, identification and model implementation. In general, any calibration strategy consists of four steps:

*MODELLING* aims at determining how many and which parameters should be used in the robot and world model.

*MEASURING* aims at measuring robot poses by an external measurement system such that sufficient information for identification is gathered or the system is persistently excited to identify the influence of error sources.

*IDENTIFICATION* step aims at updating the parameters of the robot model (see figure 2). Corrections on the model parameters are calculated to explain the measurement data. Different techniques can be worked out, such as global identification and the independent axes method.



**Figure 2: Philosophy of identification**

*MODEL IMPLEMENTATION* will compensate the task specification making use of the improved robot model.

#### 3.1 Robot Calibration

The inaccuracy of a default, manufacturer model of the system explains the difference between the simulated system response and the measured system response. In order to obtain good calibration results, it is necessary:

- to analyse the error sources and to create an appropriate model of the system,
- to assure a persistent excitation of these errors,
- and third to perform an accurate acquisition of the measurements.

The calibration step uses the measurement set in order to update the parameters of the default model and to compute the additional model parameters based. A "user defined" objective function governs the way the parameters are changed. Special attention has to be paid to model the robotic device. The robot model of the system comprises a geometrical model, either expressed in Denavit-Hartenberg [4,6] or Hyrati-Mirmirani [5] coordinates, an actuator model, and a compliance model based on a set of selected primitives.

#### 3.2 Workcell calibration

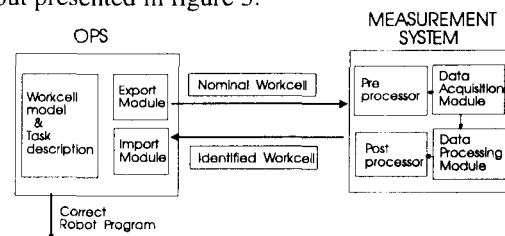
Besides a well calibrated robot, two other important conditions have to be fulfilled in order to guarantee an accurate relative positioning of the tool w.r.t. the workpiece.

- Firstly, the position and orientation of the workpiece should be accurately known w.r.t. the robot base frame.
- Secondly, the tooltip (TCPF) should be accurately known w.r.t. the robot toolframe.

Workcell calibration aims to update a nominal workcell model in order to fit the actual workcell more closely. The workcell model is composed of the position of the robot base and its tool, the measurement equipment or supporting equipment, the workpiece, and a set of programmed target positions in the robot controller.

The workcell model represents the nominal environment, i.e. the environment 'such as it is supposed to be'. However, the relative position of objects or points and (a) robot(s) in the actual workcell is likely to differ from the nominal workcell model.

Therefore, the parameters of the nominal model in the off-line programming system (OPS) should be updated such that it corresponds to the real environment. For this purpose, not only the link from measurement system to OPS is required, but also the inverse link: the nominal information of the objects to be identified can be extracted out of the CAD. This results in the system layout presented in figure 3.



**Figure 3: Workcell calibration system layout**

This concept is worked out for ROBCAD as the OPS and ENVCAL as the measurement system software.

#### 4. COMPENSATION: UPDATE OF MOTION PLANNING

Finally, the model implementation or compensation (see figure 5) enables to incorporate the calibration results into the motion programming to obtain an enhanced performance. Since most robot controllers do not allow to introduce the identified parameters and since easy, closed form equations for the identified robot will not hold, on-line calculations are not desired. Instead of changing the controller parameters, the setpoints of the operations are transformed to new setpoints, called "fake poses", in order take into account the difference between the identified model and the model on which the controller of the system is based.

Two steps are required: forward and inverse model as shown in figure 5. The inverse of the identified model enables to compute corrected joint values for the robot to reach the desired cartesian pose. The robot model in the controller, i.e. the nominal model, is used to compute the modified cartesian poses, called fake poses, to be send to the controller such that the robot reaches the desired pose.

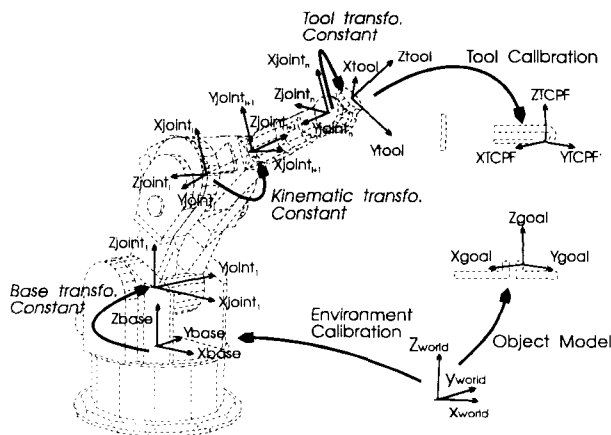


Figure 4: Philosophy of compensation

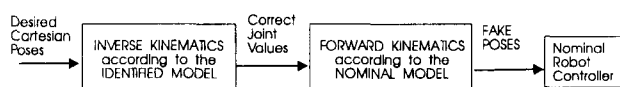


Figure 5: Principle of the Fake Pose method

#### 5. THE RESULTS

##### 5.1 Robot Performances Assessment

S/W has been developed to post-process automatically robot performances data such as pose accuracy & repeatability, path tracking accuracy, pose stabilisation and overshoot, cornering round-off errors. Different robot performance tests were conducted on the JERICO Evaluation Testbed (JET). Three diodes were mounted on the JET tool flange and measurements were acquired

autonomously using the 3D RODYN measurement system (see figure 7).

The results were processed. They showed that the initial JET accuracy was 21.6mm, while its repeatability was 0.5mm. The accuracy figure indicates the need for calibration while the repeatability figure gives a flavour on how "calibratable" was the JET system.

##### 5.2 Robot Calibration

The robot calibration s/w has been developed to calibrate any open kinematic structure, including

Dynamic positioning results	
Mean position	
X	0,096 mm
Y	0,283 mm
Z	1,000 mm
Results	
Mean distance	0,017 mm
Max distance	0,029 mm
1 Sigma	0,006 mm
Repeatability	0,035 mm
OK	

Figure 6: robot performance test results example

flexibility's effects. JET which consists of an eight axes robot was a perfect show case to assess the calibration s/w capabilities.

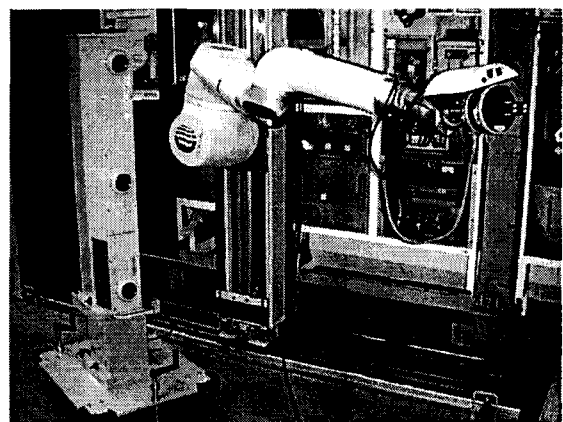


Figure 7: the JET robot and its workcell. On the left side, the RODYN6D measurement device

From the JET performance evaluation, the need for the JET robot calibration was clearly identified. The robot accuracy was 21.6mm while an accuracy of  $\pm 2$ mm w.r.t the environment was required to perform off-line programming of the JET system. The JET robot calibration was performed in two steps. In the first step, the joint zero offset of each of the eight axis robot were identified. Once identified, the joint zero offsets were up-loaded in the COMAU 3G robot controller. An accuracy performance test was run again, showing an improvement from 21.6mm down to 3.6mm. Despite the robot accuracy was much better than initially, more error

sources identification was required in order to reach the final accuracy goal.

In a second step, a new calibration session was run with more parameters to be identified. Not only different kinematic error sources were introduced such as parallelism, orthogonality or link length errors, but also flexibility's effects were considered. As a matter of fact, using the built-in library of flexible models from ROCAT, three different flexibility's sources contributed significantly to the arm accuracy. These were the elbow and wrist joints flexibility and the robot mounting plate flexibility. Taking into account all the various error sources, a final accuracy of 0.6mm was reached. This final accuracy was cross-checked from an independent set of measurement. Now that the JET robot arm was calibrated, its workcell needed to be calibrated.

### 6.3. Workcell Calibration

In order to perform "easily" the JET workcell calibration, a so-called space probe was designed. That space probe is a single point measurement device that enables an operator to digitise point in the environment. The space probe is used together with the RODYN 6D measurement device and turns RODYN6D into a portable 3D Coordinated Measurement Machine.



**Figure 8: The space probe**

The first step is for the operator to define in a script the measurement session procedure. This script is an important step as the object location that needs to be identified shall have a hierarchical structure in the workcell. For instance the sample is in a drawer, the drawer in a rack and the rack within the workcell. It is important to maintain the hierarchical structure to enable e.g. easier database maintenance or exchange of rack. Once the measurement script is written, the operator moves the space probe in the workcell to identify all interesting actuation interface location. Once completed, the measurements are post processed, and a new workcell model is generated in Robcad compatible

format. Robcad is a commercial off-the-shelf off-line programming system used for JET off-line programming. The operator loads the calibrated workcell model into the nominal workcell model. The differences between the model may then be compared. Large differences were noticed between the nominal workcell geometric model of Robcad and the real workcell geometry (up to 5cm in some cases).

### 6.4. End to End Test

Using the calibrated Robcad model and the calibrated robot model, some poses to be reached by the real JET robot were off-line define, the associated fake pose derived and down loaded to the real robot controller.

The robot controller commanded the end effector to the actual goal pose with an accuracy of about  $\pm 1.5$ mm. The end-to-end demonstration was successful.

## 7. CONCLUSION

Performance assessment and calibration enables to describe the system characteristics based on off-line processing techniques and to enhance the system performance by updating the setpoints which drive the motion controlled system. As such these techniques contribute to achieve a safe and reliable autonomous operation execution which is quite valuable especially for, but not limiting to, space applications.

Moreover, future space programs will need highly intelligent and highly autonomous systems due to the limited communication & power resources. Therefore, an accurate knowledge of the system is really necessary to pre-program & validate the operations, to guarantee a predictable execution of them, to optimise the available on-board resources and to limit operator interventions. As such performance assessment and calibration is to be considered as a supporting technology for future space application.

The necessary tools to support performance assessment and robot+workcell calibration have developed. This encompasses the necessary measurement systems, the s/w to process measurement data, the necessary drivers to up-load the robot and workcell calibration results in an Off-Line Programming system.