EXPERIMENT BASED STRUCTURAL STIFFNESS CALIBRATION OF A VIRTUAL ROBOT MODEL

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Abstract: *The main advantage of industrial robots is their flexibility, if compared to CNC machines, and speed and accuracy, if compared to humans. To improve accuracy of industrial robots, their stiffness, as one of their most important structural properties needs to be determined. As stiffness of robots with rotary joints is pose dependent, it is convenient to perform FEM simulations to predict a robot's structural stiffness in a desired pose. However, simulation results may deviate in magnitude and trend if compared to measurements. The reasons for deviations are inexact model geometry, friction, component wear and other unknown effects. Our study focuses on structural stiffness measurements for FEM model calibration. A FEM model, with all unknown effects integrated in rotational stiffness' of the robot's joints is created and for each joint, rotational stiffness as a function of joint angles is determined. The calibrated model is used to generate a surrogate model for the robot's structural stiffness.*

Key words: *Robotics, Stiffness measurement, FEM model calibration, Surrogate model*

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1. Introduction

In the era of IoT, demand for unique products is growing. It is increasingly important to produce products as fast, as unique and as accurate as possible. If machine flexibility is increased to produce more unique products, product quality and production speed are sacrificed. Thus, the future calls for more flexible machines than modern machining centres and more accurate than the available robotic mechanisms. Robotic arms show potential to compete with specialized CNC machines, but lack required accuracy to produce parts of high quality, especially when production procedure is associated with high dynamic loads (Höfener & Schüppstuhl, 2014, Klimchik et al., 2014, Iglesias et al., 2015, Mejri et al., 2015).

For optimization of production system experimental, mathematical and simulation methods are used (Kopac & Krzic, 2008, Damic et al., 2017, Zhang et al., 2017, Jurkovic et al., 2018). To improve a system its main quality characteristics need to be learned. In case of industrial robots, possibilities to improve their accuracy need to be investigated (Sabourin et al., 2012, Tratar et al., 2014, Denkena et al., 2017). Only after unknown properties become known a robotic system can be calibrated and the planned operations can be optimized (Gotlih et al., 2017, Lin et al., 2017, Lukic et al., 2017, Sun & Lian, 2018).

Many authors followed this philosophy. A full pose measurement technique of a robots end effector in Cartesian space was performed in (Nguyen et al., 2013). A set of target points was selected and measurements of end effector position and orientation with a laser tracker were performed to avoid the robot's kinematic errors during calibration. After calibration, an increased position and orientation accuracy of the robot was achieved. Proper selection of the robot's poses for calibration experiments was studied in (Wu et al., 2015). Authors proposed a new performance measure and validated the theoretical results with an experimental study. After calibration, a 5.5 times better positioning accuracy was achieved.

Effect of dynamic forces on robot's stiffness was studied in (Cen & Melkote, 2017). Authors measured the robot's Cartesian stiffness in a series of experiments, using a force scale and a laser displacement sensor. They calculated joint stiffness from the measured Cartesian stiffness with congruence transformation. An similar technique to generate stiffness maps of an industrial robot was used in (Lin et al., 2017). A stiffness performance index was defined, which can be used to analyse the robot's posture influence on its structural stiffness. The problem to design a structure with high stiffness and low mass was recognized in (Sun & Lian, 2018). Authors managed to increase stiffness of a parallel kinematic machine by three times with less than 20 % increase in mass. Topology of a robot was optimized to maximize its stiffness to mass ratio (Kim et al., 2016). The authors used metamodels to connect the part level mass and stiffness to the robot's structural stiffness.

In our study, we will focus on structural stiffness modelling, which is beside kinematic errors, the most common sources for inaccuracies, as it is present without any dynamic loads acting on the end effector. Our goal is to generate a surrogate model of a robot's structural stiffness in the joint space with regression modelling.

2. Materials and methods

ACMA XR701 robot (figure 1) was chosen for the study, being, due to its load capacity the most suitable robot in our laboratory. First, a digital model of the robot was established. As an original 3D model of the robot was not available it was generated with help of robot manufacturer's manual and data gathered by direct and indirect (3D optical) measurements. A shell model of each component was created and materials were assigned to match the robot's total mass and to achieve a realistic 3D model. The 3D model was verified with the robot's kinematic model, which was created based on the manufacturer's data and tested with the real robot's kinematics. Once the 3D model was validated, a FEM model was created based on the geometry. The FEM model was used for structural stiffness calculations, which resulted in very low deflection values, indicating the necessity to calibrate the model. The results of the first calculation are presented in table 1.

Pose	q2 [deg]	q3real [deg]	q4 [deg]	q5 [deg]	Z def. [mm]
5	-35	40	0	0	0.00022
41	5	77.5	0	0	0.0002
77	45	115	0	0	0.00027

Tab. 1. Postures and Z deflection simulation results

Magnitude of deflection in Z direction (vertical direction) indicated the need to verify the result on measurements. At the same time, an interesting phenomenon was observed. With distance from the robot's main Z-axis (vertical direction through the robot's first axis), deflection is not steadily raising. Instead, minimum deflection was found at pose 41 (table 1), which is located most central in the robot's workspace.

2.1 Stiffness measurements

In the second stage, a stiffness measurement experiment was set up. Same load as for simulation was applied to the robot's mount plate at the end effector position to replicate the simulation environment. A digital micrometre was used to measure end effector deflection in Z direction. The experimental setup is presented on the figure 1. To model the effect of axis rotation on robot's structural stiffness, an experiment with boundary values presented in table 2 was designed.

Fig. 1. Structural stiffness measurements on ACMA XR701

	Min. [deg]	Mid. [deg]	Max. [deg]
q2	-35	5	45
q3real	40	77.5 (60)	115 (77.5)
q4	-200	0	200
q5	-100	0	100

Tab. 2. Boundary values for structural stiffness measurement

q2, q3real, q4, q5 are joint 2, 3, 4 and 5 rotations, while minimal and maximal values in table 2 are representing joint rotation boundary values. q3real is used instead of the actual q3 rotation angle, because the robot's structure has a kinematic parallelogram included. Consequently, q3 does not represent the actual angle between the second and the third link, hence q3real is more convenient to use.

Another consequence of the kinematic parallelogram is kinematic dependency of q3real on q2, practically meaning that at specific q2 values some q3real values do not exist. To describe the most of the robot's workspace with a manageable number of experiments a full factorial experiment with four factors and three levels had to be adjusted to use the middle and maximum values for q3real, which are the values presented in brackets in table 2 for experiments where $q2 = -35^\circ$. The final matrix consists of 81 experiments. From all experiments, some were inaccessible, therefore nine reference points were selected from the complete matrix. The selected measurement points are presented in table 3.

Experiments with three different external loads were repeated three or six times. 150 N, 375 N and 650 N loads were used, where the last load is half of the robot's maximum load capacity. Averaged measurement results are presented in figure 2. Measured magnitude of deflection in Z direction is 10^5 times higher compared to simulation results in table 1. Measured deflection results show a similar trend as already observed for simulation results, with a minimum deflection value located at the medium end effector distance from to the robot's main Z axis. Another interesting observation is that applied load and deflection are not linear. In the following chapters only 650 N load case are discussed.

Pose	q2 [deg]	q3real [deg]	q4 [deg]	q5 [deg]
3	-35	40	-200	100
4	-35	40	0	-100
5	-35	40	0	0
39	5	77.5	-200	100
40	5	77.5	0	-100
41	5	77.5	0	0
75	45	115	-200	100
76	45	115	0	-100
77	45	115	0	0

Tab. 3. Selected poses for structural stiffness measurements

Fig. 2. Deflection measurement results for reference point

2.2 Virtual model calibration

Based on measurement results a calibration of the virtual model was performed. A FEM model corresponding to each robot's measurement pose was created and rotational stiffness as a parameter was introduced in each joint as shown in figure 3. Rotational stiffness as a function of joint angle was introduced to incorporate unknown effects, causing the difference between simulation and measurement results.

To find the dependency between axis rotation and rotational stiffness a two-stage optimization procedure was designed. In the first stage, a sensitivity study was performed to determine the most dominant joint effects. Boundary values for low and high rotational stiffness were set to 10^5 - 10^6 N m/rad.

Results of the study for poses 5, 41 and 77 are presented in figures 4.

Fig. 3. Virtual model with rotational stiffness parameters and force boundaries

Fig. 4. Rotational stiffness effects on deflection results for poses 5, 41 and 77

Rotational stiffness 2 has a dominant effect on deflection for all poses, followed by rotational stiffness 3 and 5 and rotational stiffness 4 with almost no effect. In the second stage, a three step parametric study was designed to reduce the number of experiments required for calibration. In the first step rotational stiffness 2 and 3 were calibrated on poses 5, 41 and 77. For the remaining six measured poses, only values for joints 4 and 5 were changed. A two factor, ten level parametric study with the same boundary values as those used for the sensitivity study was created, resulting in 100 experiment runs. This study setup allows adding experiment runs in case of required refinement.

In the second step, poses 4, 40 and 76 were calibrated in a similar way. Rotational stiffness values for joints 2 and 3, determined in the first step were set in the model and only rotational stiffness values for joint 5 were changed. Ten experiments were used. In the third step poses 3, 39 and 75 were calibrated. Rotational stiffness values for joints 2, 3 and 5, determined in the first and second step were set in the model and only rotational stiffness values for joint 4 were changed. Ten experiments were used.

Symmetry points for joints 4 and 5 were added and the rotational stiffness' with the best matching deflection results for each pose were used to fit a regression model connecting rotational stiffness' and joint angles. A sixth degree regression model was chosen to achieve a perfect fit, preserve a natural shape of the response surfaces and reduce gradients in case of small rotations. Results for pose 1 are presented in figures 5. Red points represent optimized rotational stiffness values, while the green planes represent dynamically fitted response surfaces.

Fig. 5. Response surfaces for pose 1 of rotational stiffness' versus joint angles

3. Results and discussion

Finally, the generated rotational stiffness models were integrated into the robot's FEM model and the calibrated model, which was used to calculate the remaining cases of the adjusted full factorial experiment matrix. Main effects of joint angle rotations on deflection results were studied and a structural stiffness surrogate model for the robot was created, by regression modelling.

3.1. Main effects

Main effects of joint angle rotation versus normalized structural stiffness are presented in figures 6. Red curves represent maximum values, green curves represent averaged values and blue curves represent minimum normalized structural stiffness values. q_2 effect on normalized structural stiffness shows the expected behaviour. Structural stiffness reduces with distance from the robot's base as showed by the minimum curve, but also the average and the maximum curve are close to the expected behaviour. The adjustment of experiment matrix and consequently lack of experiment orthogonality could be the main reason for the unexpected behaviour. The average curve for q_{3real} shows a good agreement with the expected behaviour. An unexpected drop of maximum structural stiffness is observed at 60° angle, which is not reflected by the average curve, as minimum curve is raised at that angle. Lack of orthogonality is likely the reason for this behaviour. q_4 has almost no influence on the robot's structural stiffness. q_5 shows an interesting behaviour. For some postures, maximum stiffness can be achieved at $q_5=0^\circ$, but stiffness drops quickly with robot's posture change. This indicates that q_5 does not have a dominant effect on the robot's structural stiffness. Stable conditions can be achieved close to q_5 boundary values, which is convenient as for $q_5=0^\circ$ the robot is also in its singularity state.

Fig. 6. Main effects of joint (2-5) rotation angle on normalized structural stiffness

3.2. Surrogate model for robot's structural stiffness

The robot's kinematic workspace cross section was equipped with its structural stiffness values to generate three dimensional structural stiffness maps. The cross section is three dimensional due to the fourth joint rotation, which moves the end effector point outside the Y zero plane. Warm colours represent high stiffness, while cold colours represent low stiffness. In figures 7, two viewpoints at the same stiffness maps are presented.

The most interesting conclusion regarding figures 7 is that there are regions in the middle of the robot's workspace, where the lowest and the highest structural stiffness are close by. Overall, the results are expected, with low structural stiffness observed at high distance from the robot's main Z-axis and at increased robot's stretch.

Fig. 7. Structural stiffness map of ACMA XR701

4. Conclusion

The presented paper offers insight into structural properties of an industrial robot. To generate a model for structural stiffness prediction of an industrial robot, a FEM model calibration technique based on structural stiffness measurements and regression modelling was presented. The technique consists of geometrical data acquisition, 3D modelling, 3D model verification, FEM modelling, FEM model verification, stiffness measurements, FEM model calibration and surrogate model creation.

Our conclusion has been that a simple FEM model based on the robot's geometry was not well suited for structural stiffness prediction. Due to geometrical and physical properties of the structure, which could not be accurately included in the model, e.g. friction and wear, the results of the preliminary FEM model were far from the measured results. Experiments to gather relevant data from the actual robot and consecutive parametric studies were performed to calibrate the virtual model. A dedicated set up for robot's stiffness measurements would enable gathering more data to increase calibration quality. Because FEM analyses require skilled engineers for set up and lots of calculation time, a surrogate model for the robot's structural stiffness was created. Main effects were analysed revealing good agreement with the expected behaviour. Observed exceptions were linked to the lack of orthogonality in experiment design, originating from the robot's kinematic structure.

Our conclusion from the structural stiffness maps was that some regions in the robot's workspace are accessible with poses that have far superior structural stiffness to others. With this in mind, an end effector can be mounted to enforce the robot's structural stiffness for a specific task, while the task itself can be optimized on structural stiffness. Our future research will focus on generating kinematic and dynamic performance maps of the robot, to describe the robot's kinematic and dynamic properties.

5. References

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