Fusion Engineering and Design 86 (2011) 1958–1962

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

A method for enabling real-time structural deformation in remote handling control system by utilizing offline simulation results and 3D model morphing

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ARTICLE INFO

Article history:
Available online 30 December 2010

Keywords:
ITER
Remote handling
Divertor Test Platform 2
Virtual engineering
Flexibility
Deformation
Morphing
Virtual reality

ABSTRACT

A full scale physical test facility, DTP2 (Divertor Test Platform 2) has been established in Finland for demonstrating and refining the Remote Handling (RH) equipment designs for ITER. The first prototype RH equipment at DTP2 is the Cassette Multifunctional Mover (CMM) equipped with Second Cassette End Effector (SCEE) delivered to DTP2 in October 2008. The purpose is to prove that CMM/SCEE prototype can be used successfully for the 2nd cassette RH operations. At the end of F4E grant "DTP2 test facility operation and upgrade preparation", the RH operations of the 2nd cassette were successfully demonstrated to the representatives of Fusion For Energy (F4E).

Due to its design, the CMM/SCEE robot has relatively large mechanical flexibilities when the robot carries the nine-ton-weighting 2nd Cassette on the 3.6-m long lever. This leads into a poor absolute accuracy and into the situation where the 3D model, which is used in the control system, does not reflect the actual deformed state of the CMM/SCEE robot. To improve the accuracy, the new method has been developed in order to handle the flexibilities within the control system's virtual environment. The effect of the load on the CMM/SCEE has been measured and minimized in the load compensation model, which is implemented in the control system software. The proposed method accounts for the structural deformations of the robot in the control system through the 3D model morphing by utilizing the finite element method (FEM) analysis for morph targets. This resulted in a considerable improvement of the CMM/SCEE absolute accuracy and the adequacy of the 3D model, which is crucially important in the RH applications, where the visual information of the controlled device in the surrounding environment is limited.

1. Introduction

The paper presents how the load compensation functions have been implemented in the control system software to improve the absolute accuracy and visualization accuracy of DTP2 control system. It also proposes a new method for accounting structural deformations in DTP2 control system through 3D model morphing, utilizing the finite element method (FEM) analysis results for morph targets. In addition to the actual component morphing, the 2D texture morphing will be utilized for representing the structural load per each component for better operator evaluation.

During the 2nd cassette installation process, CMM travels into radial direction, towards the reactor, on top the maintenance tunnel rails with the aid of an electric motor drive, Fig. 1. The lifting and tilting motions in the vertical plane are used for controlling the position and orientation of the cassette according to uphill profile of the maintenance tunnel. The SCEE, which consists of the cantilever (CRO) and the hook-plate (HRO) rotational joints, is devoted to change the position and orientation of the cassette during the toroidal motion towards the place of the 2nd cassette.

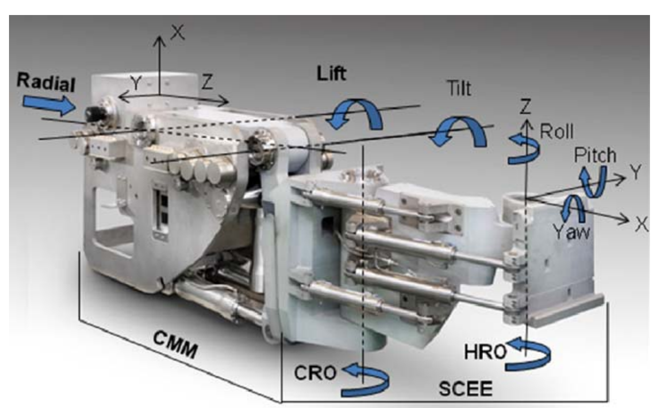

Fig. 1. CMM and SCEE structural representation.

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doi:10.1016/j.fusengdes.2010.11.015

2. Content of DTP2 deflection studies

2.1. CMM/SCEE trials

After delivery of CMM/SCEE to DTP2, the system integration phase was started in order to prepare the system for the actual testing. This testing was done in two phases starting from the factory floor and ending to the RH operated tests from the control room [1].

The initial motion programs for the cassette operations were done by teaching, while having a continuous visual contact with the cassette. Good repetition accuracy (3 mm) of the CMM/SCEE guaranteed successful repetition of the motion programs. However, static 3D model could not support operations properly, because of poor absolute accuracy of CMM/SCEE. On the grounds of 3D model, it seemed that the cassette was colliding with Divertor Region Mock-up (DRM) structure although in practice everything was fine. It was very clear, that absolute accuracy of the system should be improved before the remote operations could be started.

2.2. Load compensation

The effect of load to the CMM-SCEE kinematic chain (body, wheels, links and joints) was measured during the motion programs. And it was realized that the positioning error at the tip of the cassette was in the worst case close to 80 mm. The measurement data was utilized for creating load compensation functions to improve the absolute accuracy. The solution is general for the RH maintenance tunnel operations, but for the toroidal operations the load compensation model is a look-up table based on the values of the CRO joint. The compensation approach is simple and well reasoned because of generality for CMM to support future CMM operations with other end effectors. The specific look-up tables are used only when operating with SCEE for performing a specific toroidal trajectory in and out. The compensation functions helped to improve the performance of the equipment considerably. Thus, the positioning error at the furthest point of the cassette was reduced from almost 80 mm to about 5 mm [1].

The implementation of load compensation into the cartesian reference values can be seen in Fig. 2. The solution is divided into two phases depending on whether the cassette is loaded to the HRO or not. 'Cartesian reference for ideal equipment' (Fig. 2) is expressing the location of a coordinate system (Fig. 1) which coincides with the axis of the HRO joint. Thereby, HRO joint can be used only for changing the orientation of the cassette around the vertical axis and only the CRO joint can be used to reach a y-coordinate value of the reference data. For this reason, the load compensation functions during the toroidal motions depend on the CRO joint.

If there is no load in HRO joint, an inverse kinematics solution can be used directly to solve corresponding values for the joint references. The solution is calculated using the Denavit–Hartenberg parameters, which include corrections based on the signature calibration of the CMM/SCEE [1].

When the load is attached to the HRO joint, the inverse kinematics solution cannot be used directly because in this case the cartesian reference includes also the components that represent the deflections of CMM/SCEE. When the effect of load is known, the correct value for CRO joint can be found either iteratively utilizing the inverse of the load compensation or by defining the least-square polynomial fit between the measured y-coordinate values and the corresponding CRO joint values. Both iterative solution and 7th order polynomial fit are working well in practice. After the CRO joint value is defined, the position compensation in the x-, y- and z-directions and the orientation compensation in the Roll- (R) and Pitch- (P) directions can be made with respect to the cartesian reference. The compensation movement in the Yaw (W) direction cannot be done because of lacking the ability to move in the yaw-direction with the CMM/SCEE.

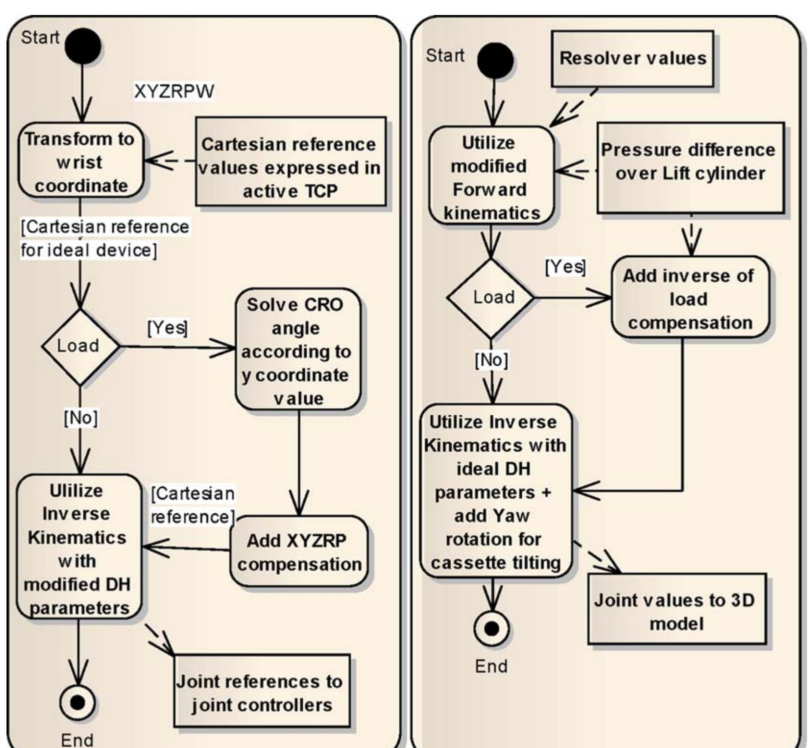

Fig. 2. Left: load compensation in cartesian space. Right: implementation of load effect to the joint data of the real device.

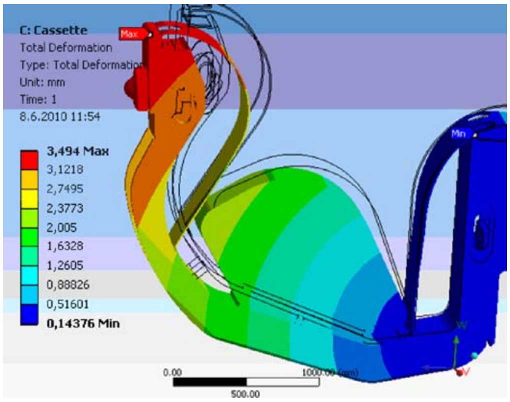

Fig. 3. Ansys FEM result (DCM lifted from RH interface).

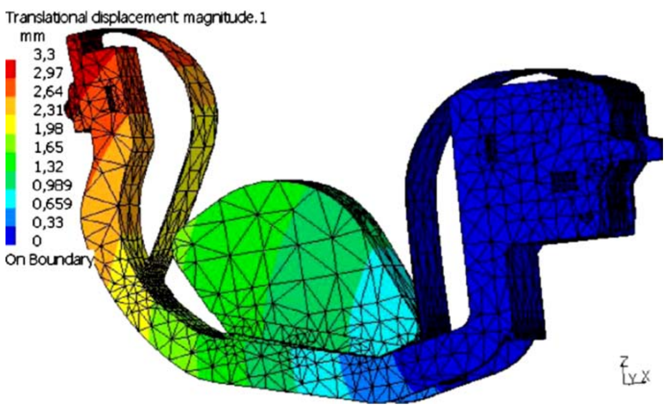

Fig. 4. CATIA FEM result (DCM lifted from RH interface).

2.3. Improving teleoperator visualization accuracy

Tilting the cassette in the yaw-direction can be visualized when an additional joint is added to the 3D model of CMM/SCEE, (Fig. 2). This joint has been placed between the hook plate and cassette. Because of that, the operator can see the effect of the cassette tilting, which is 10 mm at the end of toroidal movement in the vertical direction.

To increase the visualization accuracy, when the cassette is contacting the inner and outer rails of DRM, the pressure difference over the Lift cylinder provides estimation about the load, as the weight of the cassette is gradually transferred from the hook plate to the DRM rails or the other way around, (Fig. 2).

2.4. Calculation of the deflections of the Divertor Cassette Mock-up

In the real operation environment, the shape of the Divertor Cassette Mock-up (DCM) is never equally represented by the 3D-CAD model. The DCM deflects, when it is handled with the CMM end-effectors and when it rests on the toroidal rails (Figs. 3–5).

The deformations of the DCM were calculated using Ansys software and CATIA FEM-tools. The results of these two calculations were compared. In conclusion, both FEM tools provide similar results if the restraints are specified correctly.

In the next phase, the FEM results were divided to components. Then horizontal and vertical deflections of the hook plate handling and resting on the toroidal rails were compared to measurements that had been done for real DCM in the DTP2 laboratory (Table 1). The measurement device is Sokkia NET05 high precision 3D coordinate measuring system (theodolite).

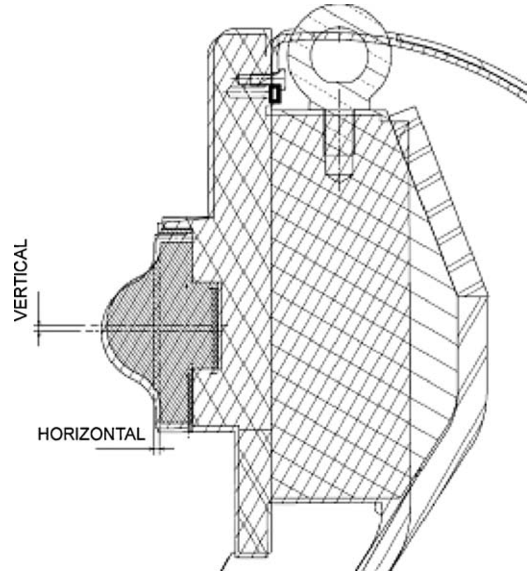

Fig. 5. Vertical and horizontal deflections in respect to cassette structures.

Comparison between the FEM results and the Sokkia measurements showed that the real DCM behaves as it was analyzed.

2.5. Visualization of the deflections of the Divertor Cassette Mock-up

Design of the DCM has been made according to applicable design rules and standards of the machine design. As a result, the stresses are always below the proportional limit of the construction material and the behavior of material is linearly elastic. The initial tests in this study were conducted under the Hooke's law assumption for linear deformations.

Hence the results of the FEM analysis can be utilized for the visualization of the DCM deformations. Problem of loaded device shape not being reflected to the teleoperator view makes accurate control of the system near impossible. Teleoperator visualization by accounting deformations can be carried out in two different ways. The traditional method is to divide a body into pieces and to create the link mechanisms between the pieces [4]. This approach requires a lot of analysis work. The position of the joints and the maximum joint values are the result of these analyses. Based on the analyses, it was recommended to divide DCM into three links, which were connected with two rotational joints, Fig. 6.

Method proposed by this paper is to use the 3D morphing – the process of gradual transformation between 3D bodies – to describe the deformations of the body based on the FEM analysis results. The metamorphosis or the (3D) morphing of the 3D graphical objects, also known as shape interpolation, is the process of transforming one shape into another [2]. This technique allows utilization of the FEM analysis results directly without laborious link-joint approximations. In addition, this method enables the use of sep-

Table 1
FEM results compared to Sokkia measurements.

DCM deflections			
Criteria	Horizontal	Vertical	Unit
Total deformation based on FEM between hook plate handling and resting on toroidal rails	7.2	9.2	mm
Sokkia measurements between hook plate handling and resting on the toroidal rails	6.6	7.3	mm

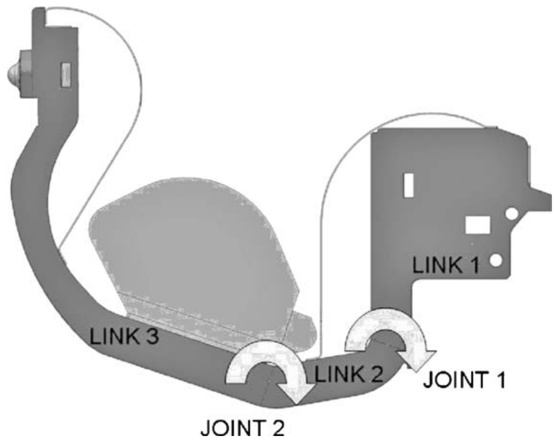

Fig. 6. The body of the cassette is divided into three rigid links connected with two rotational joints to approximate mechanical flexibilities.

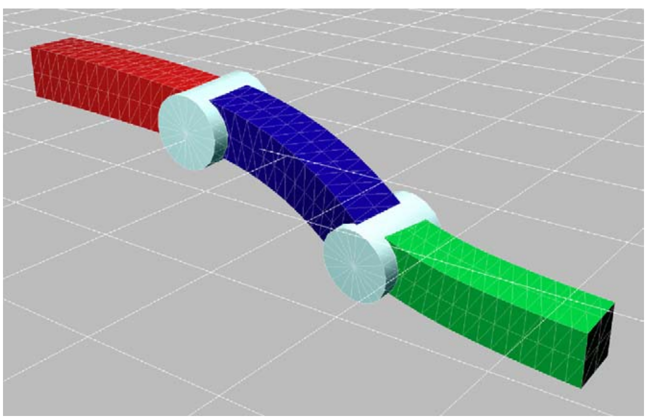

Fig. 7. Simplified example of 3 links deformed by 9 individual morph targets (forces).

arate deformation results by utilizing FEM results for each morph target per force applicable to the component for a given scenario (Fig. 7). This provides a high degree of adaptation capabilities for accounting a large variety of flexibilities in complex systems where multiple sources of forces can affect each part of the system.

For morphing the model, we have used the linear interpolation between the vertices in the non-deformed 3D model and the deformed FEM model. A more advanced morphing algorithm is the strain field interpolation [3] if the accuracy of the linear interpolation is not sufficient for the given application.

For visualizing the deformations to the teleoperator, Dassault Systems Virtools 5.0 was used (Fig. 8). The virtual environment is built by directly utilizing ITER CATIA models in conjunction with the FEM models that are utilized for creating morph targets.

The benefits of the proposed method are the following:

- Application of the fully flexible mesh morphing between the components unloaded neutral states and the deformed states for a given maximum force per morph target thus directly utilizing the FEM results, Fig. 4.
- Easier reuse of the existing deformation data obtained by the offline and online analysis of real systems.
- More accurate representation of each section of the complex system components and full control over the continuum possible deformation points, instead of rough estimations gained trough joint-link approximation.
- Possibility to combine multiple deformations separated by individual forces in complex system.

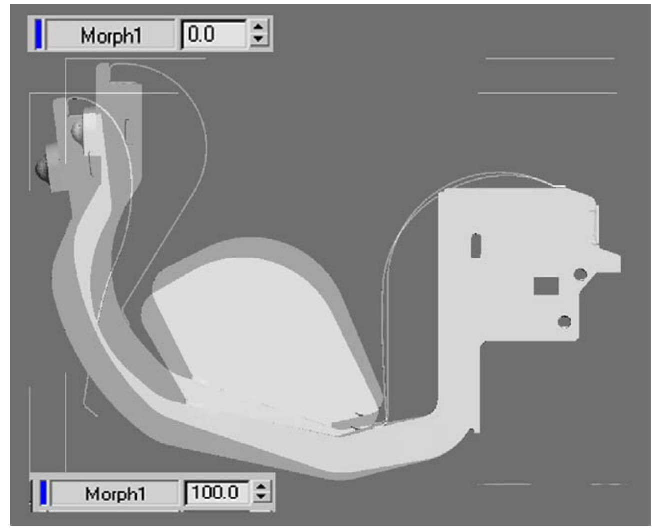

Fig. 8. Example of DCM morph targets within virtual environment.

2.6. Controlling of the 3D model deformations

Controlling the 3D model deformations means that the deformations in the virtual environment have to follow the actual deformations. The deformation information can be determined based on the previously measured deformations for a given operation state or by using the hydraulic system pressures to estimate the force, hence utilizing existing sensor information.

In the case of robot operations, a more accurate solution can be achieved by employing strain gauges to measure the actual deformations of the robot links. In the laboratory tests, the strain gauges will be installed to the DCM.

The advantage of the strain gauges includes:

- Complementarity to the morph target method, where for each force one can have an individual morph target controlled by a dedicated strain gauge.
- Ability to measure the exact deformations immediately, not relying on the previously measured static deformation data or hydraulic pressures that may not be available for all force directions.

3. Future work

The continuation regarding the fully flexible 3D virtual prototyping of the DTP2 robot components will be as follows. Initially, the DCM flexibility studies will focus on solving the flexibility problems of subsystems. Later, the studies will cover the whole CMM robot structures and will result in appropriate joint structures of the rigid objects to reflect the deformed states of the preceding objects in the link chain.

More sophisticated morphing methods such as the 3D strain fields in replacement of the linear interpolation will be applied. This will be combined with the flexible 3D virtual prototype to be controlled by the strain gauges measurements of the real DCM deformations.

We will further analyze the combined and separate effect of the flexibility of the robot links and the joints. This will help to create a more precise FEM models. Finally, the influence of the link flexibilities on the dynamic response of the system will be explored.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Acknowledgements

This work is supported by the European Commission under the contract of association between EURATOM/TEKES, was carried out within the frame-work of the European Fusion Development Agreement.

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