Reduce vibration and improve positioning accuracy of a two-axes Gantry Robot using co-simulation between Abaqus and Dymola

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Abstract: *This document gives an overview on the coupling between Abaqus and Dymola. Then a practical example of co-simulation is developed. This example will focus on decreasing vibration and improving positioning accuracy of a gantry robot.*

Keywords: *Gantry Robot, System Modeling, Control System, Co-simulation, Multi-Body Dynamics, Vibration*

1. Introduction

Gantry robots are also called cartesian or linear robots. They are usually large systems that perform pick and place applications, but they can also be used in welding and other applications such as palletizing, machine loading and automated assembly.

Gantry robot systems provide the advantage of large work areas and better positioning accuracy. Position accuracy is the ability of the robot to place a part correctly. Position accuracy is mainly impacted by the vibration of the end-effector.

Minimizing the vibration of the end-effector of gantry robots is an important design constraint to achieve good position accuracy. That’s why most of the existing gantry robots are designed and constructed in a way to maximize their stiffness by using heavy material. However, the existing heavy rigid manipulators are shown to be inefficient in terms of power consumption and speed required with respect to the operating payload (Dwivedy, 2006).

In order to improve industrial productivity, it is required to reduce the weight of the arms and/or to increase their speed of operation. For these purposes it is very desirable to build flexible robotic manipulators. However, the operation of high precision robots is severely limited by their dynamic deflection, which persists for a period of time after a move is completed. The settling time required for this residual vibration delays subsequent operations, thus conflicting with the demand of increased productivity. These conflicting requirements between high speed and high accuracy have rendered the design of gantry robots task a challenging problem, either for researchers and industrials. Indeed, integrated design of the control system of flexible robots and the physical plant is not an easy task.

Several previous works were interested in the control of flexible robots. For instance, authors in (De Luca, 2000) considered two model classes of flexible robots: robots with flexible joints but with rigid links and robots with flexible links. For the second class of models, authors in (Cannon, 1984) suggest to use reduced-order control and adaptive control methods. The use of reduced-order models requires that the system's model should be linearizable, which is not usually the case. The second solution is the use of non-linear adaptative control (Yang, 1997). Nevertheless, to develop accurate controllers, the mechanical part of flexible robot should be as accurate as possible, since the software environments for designing controllers do not support the 3D definition of the mechanical system.

Co-simulation between design tools supporting the design of controllers and finite element analysis method is an interesting solution to integrate both the design of control and physical systems.

In this paper, we propose a co-simulation method based on Dymola and Abaqus. This method was applied to the analysis of a gantry robot. This study was performed in a context of collaboration between DPS and Supméca as part of PLACIS project. This paper is therefore organized as following: the section Abaqus-Dymola co-simulation will give an overview on this specific simulation technique, then the section Gantry-robot will focus on the application example and how the system was modeled. Finally the section Results will discuss about the simulation results.

2. Work context

2.1 Digital Product Simulation

Digital Product Simulation (DPS) is initially a French company founded in 1997 by Mr. Patrick Grimberg based on the observation that Computer Aided Design (designers) and Computer Aided Engineering (analysts) were 2 different worlds within the industry evolving in different environments as well as not sharing knowledge and data.

DPS realized, early on, that analysis and simulation may play an important role in improving and leveraging industrial products design processes both from a technological (more room to innovation) and commercial (time & money gains) perspective.

Throughout the years, DPS has acquired a reputation for excellence in CAD & CAE integration, process automation as well as leveraging it with numerical optimization techniques. We have specialized in providing tools and consulting to ultimately enable "Simulation-Based Design".

As a matter of fact, DPS grew significantly opening first an office in Toulouse, France mainly focused on the aerospace industry. In a second time, willing to expand its growth at an international level, DPS decided to focus on the North American and Japanese markets, driven by the tremendous implantation of automotive industry in those world areas.

DPS has a strong partnership with Dassault Systemes, the software editor of CATIA V5 among many other products that provides DPS the capability to develop add-on tools fully integrated to CATIA V5 as well as to resell part of Dassault Systemes' portfolio.

Following DS acquisition of Dymola in 2006, DPS started reselling the product in France then enlarging DPS scope capabilities to systems modeling i.e. 0D/1D simulation as well as systems engineering. This evolution has been substantially motivated by the development of Product Lifecycle Management (PLM) platforms such as CATIA V6 for instance.

Both having expertise in Finite Element Analysis (FEA) and behavioral modeling and simulation (0D/1D), this is naturally that DPS started investigating on coupling capabilities between both simulation worlds therefore to study co-simulation techniques. This aspect will be developed further in this paper focusing on how Abaqus (3D FEA solver) and Dymola may interact each other.

2.2 Supméca

Supméca is a French engineering school, located in Sait-Ouen (France) delivering the "Diplôme d'Ingénieur de l'Institut Supérieur de Mécanique de Paris" equivalent to a Master's Degree in Science and Engineering.

Combining high level academic classes with a significant experience in the industry, the engineering curriculum in Supméca aims at maintaining tight links with the business world requirements. During the 3-year curriculum 11 months are dedicated to internships. More than half of the students take this organization as an opportunity to go and intern abroad. The curriculum includes mandatory and optional scientific courses; economic science courses, social and human science courses as well as two mandatory foreign languages including English, during the 1st and 2nd year, and customized options during the 2nd and 3rd year.

Nevertheless, Supméca is and remains a mechanical engineering school axing its curriculum on mechanics with a specialization within 3rd year on systems and numerical simulation.

2.3 PLACIS

PLACIS is a program for Master Students aiming to establish a new format to train engineers through at-a-distance international and/or industrial multidisciplinary projects carried out collaboratively by students using the last engineering tools and the new 3.0 semantic and collaborative platform developed within PLACIS (François, 2015).

Purpose of PLACIS is to enable collaboration between an industrial partner and a university following a project's proposal by the company. This project has preferably to require expertise from different engineering fields and will involve students gathering within a team to carry out the project while staying in their home university, exchanging data and using the tools of collaborative engineering.

Tutoring is managed by their teachers and the industrial company providing the subject which leads to a performance (models, report, presentation…) being assessed by both industrial partners and teachers.

As a matter of fact, Digital Product Simulation proposed a subject within PLACIS scope to Supméca who brought on board a team of students being part of 3rd year systems and numerical simulation option. The topic, proposed by DPS aims to study the feasibility of implementing a co-simulation process between Dymola and Abaqus then to define overall methodology therefore applying this procedure for industrial use cases.

3. Abaqus-Dymola co-simulation

Co-simulation is a technique that enables dialog between different numerical models, themselves based on different modeling scales, spatial or temporal, or diverse physical domains: thermal, mechanics, fluid, control command and many more.

The principle is to combine into one global model several submodels that focus on specific physical domains or different engineering fields. Usually, it consists in coupling a plant model i.e. that contains the physical behavior of the system (this model could be whether a FEA model or an equation-based analytical model) with a logical control model that could be compared to an algorithm implementation within a simulation tool.

Ultimate goal of such an approach aims to introduce analytical logic within multi-physical systems simulation to utilize each software/tool's environment at its fullest potential.

In the case of this paper, we are focusing on co-simulation between the following simulation tools: Dymola and Abaqus, here are some guidelines and advice to ensure best practice and perform a good co-simulation using those two environments. This technique can be used to solve complex systems that include electronics such as control systems, electro-mechanics, hydraulics, and pneumatics.

3.1 Dymola

Dymola is a physical modeling and simulation tool, used in automotive, aerospace, energy, robotics, packaging, process and other industries.

Dymola rapidly solves complex multi-disciplinary systems modeling problems that can contain a combination of mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented characteristics and components.

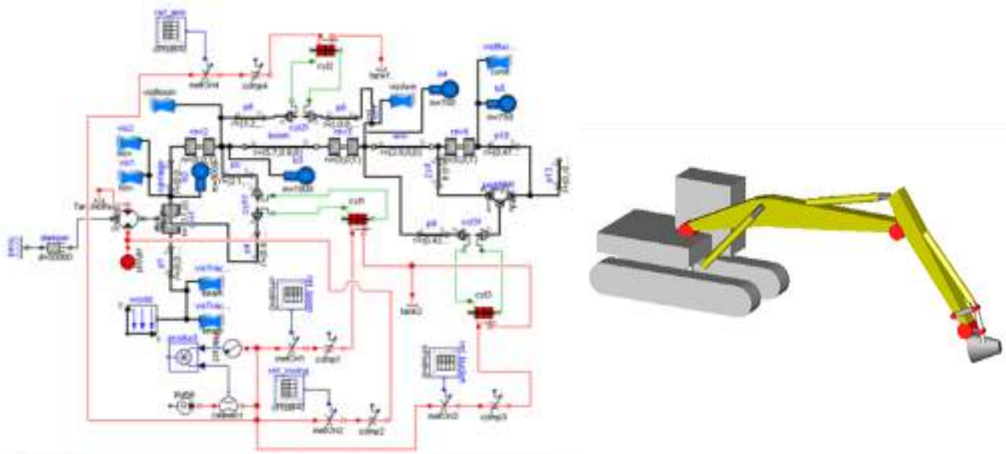

Figure 1. Example of Dymola model: Excavator with mechanical and hydraulic parts (left Dymola model and right system's 3D animation)

3.2 Abaqus vs. Dymola

Abaqus and Dymola have different modeling abstraction:

- Logical modeling: refers to a large class of modeling abstractions that is often encountered in engineering practice. The logical model is a technical implementation to fulfill the functional architecture. It contains different components and the interface of these components. It defines the organization of the system using diagrams, the relation between the sub-systems through their port and the behavior of the system and its components. Dymola focuses mostly on this modeling abstraction.
- Physical modeling: is the complementary modeling abstraction to logical modeling. An FEM application such as Abaqus uses a physical modeling abstraction most of the time: as finite elements deform they know precisely about their geometry thus trying to mimic the real world at a fine-grain level.

3.3 Applications

The goal is to use the core strengths of the two analysis software: physical modeling capabilities in Abaqus together with the logical modeling features in Dymola.

Logical-physical modeling is well suited for mechatronics system analysis. These systems are a combination of different fields, mechanical engineering, electronic control and computing. Co-simulation addresses a way to solve these complex systems.

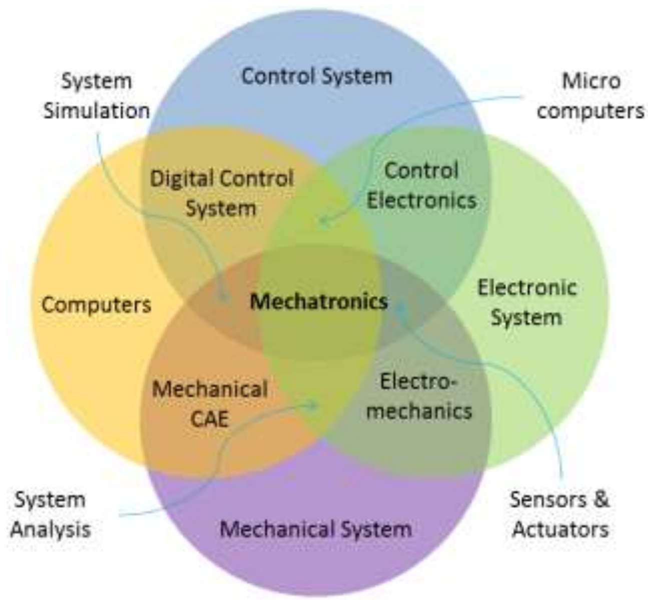

Figure 2. Mechatronics shown as multidisciplinary field of engineering

The physical system modeled with Abaqus is furnished (in Abaqus) with sensors and actuators to create what is commonly referred to as the Plant. The sensor data computed by Abaqus is passed to Dymola (the Controller), which computes the needed actuation to drive the physical system in the desired state.

In this way you can control in a sophisticated way the loads (actuation) applied to your Abaqus model to achieve the desired position, deformed shape, etc. In addition, in Dymola you can model electro-magnetic entities such as electric motors, magnetic brakes, etc. Examples include controlled deployment of landing gears in the aerospace industry, automotive electronic control modules for airbag deployment, robotics, or even modeling of electromagnetic forces in speaker systems.

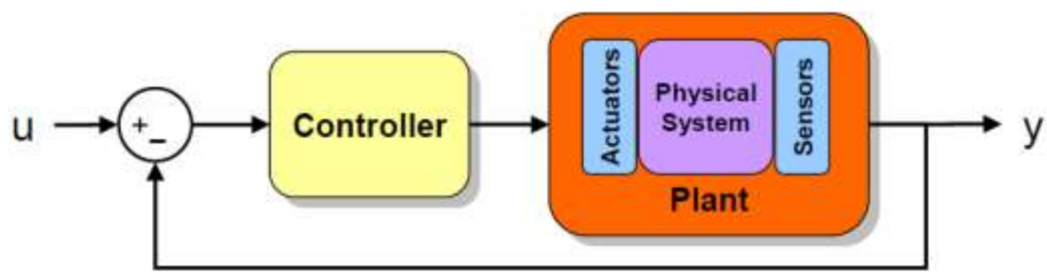

Figure 3. A logical-physical model flow

3.4 Co-simulation procedure

As for every co-simulation, man has to define connectors for each model in order to enable them to share data (outputs of one model will be inputs of the other one). To do so slight modifications must be performed onto the Abaqus model:

- Identify Abaqus model inputs i.e. actuators
- Identify Abaqus model outputs entities i.e. sensors (nodes, connectors…)
- Add all Abaqus cards needed to get a correct setup (`*CO-SIMULATION`, `*OUTPUT` for sensors, `*AMPLITUDE` for actuators)
- Define data exchange's strategy and step time

Here are some guidelines for Dymola model's preparation as well:

- Include input and output blocks within Dymola model
- Define parameters for the solver within Dymola environment

User has then to define a mapping file to let co-simulation process know that an input will match with an output and not another one.

This process can be initialized whether by launching it manually using DOS commands or through automated functionalities available in Abaqus/CAE software. Either method does not impact results quality and will provide the same results for one model.

4. Gantry robot

4.1 General presentation

Gantry robots are robots built atop a gantry that allows movement across a horizontal plane. They are also called Cartesian or linear robots. These kinds of robots are used for various applications:

- Machine Tending
- Materials Handling
- Stacking / Palletizing

Gantry robot systems provide the advantage of large work areas and better positioning accuracy. Position accuracy is the ability of the robot to place a part correctly. Gantry robots are easier to program, with respect to motion, because they work with an X, Y, Z coordinate system. Another advantage is that they are less limited by floor space constraints.

Figure 4. Left a 3 axis gantry robot and right a 2 axis gantry robot (source: http://www.uskoreahotlink.com/products/manufacturing-and-machinery/factory-automation-systems/).

4.2 Robot Abaqus Model

A 2D representation of the gantry robot proposed for this study is given in figure 5.

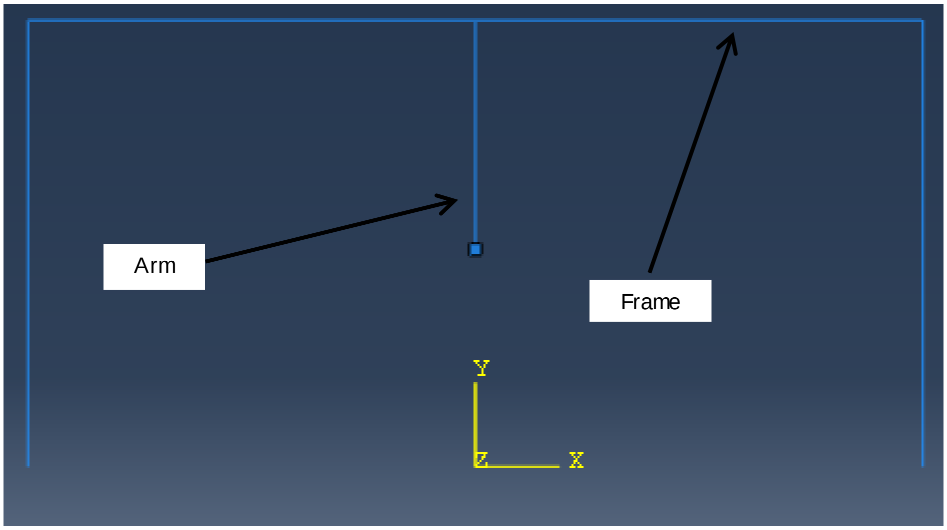

Figure 5. 3D model describing the studied gantry robot

The robot is composed with a frame and an arm. The horizontal frame is 8 meter long and the vertical length is 4 meter. The frame profile has a 200mm x 200mm rectangular section with a

10mm thickness. The arm is 2 meter long with 150mm x 150mm rectangular section profile and a 10mm thickness.
Friction behavior has been added to the connection between the arm and the frame. Finally, the arm has 1 translational degree of freedom.

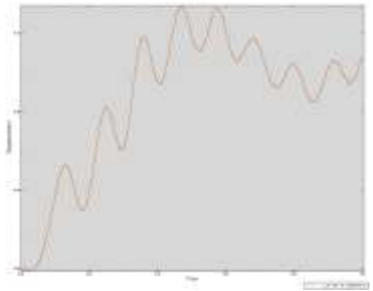

Figure 6. Arm's displacement when an instantaneous force is applied

In this model, arm's top node's displacement and velocity is measured using sensors. A concentrated force driven through an actuator is then applied to this same node. To summarize, Abaqus model has one input and two outputs.

Figure 6 shows arm's displacement when an instantaneous force is applied. On this plot vibration is clearly visible. The goal is to couple Abaqus model with Dymola model to find a good control set minimizing arm's vibration.

4.3 Robot controller model in Dymola

Dymola model is used to control robot's arm's behavior. Following Abaqus model definition, the control model has two inputs, displacement and velocity and one output, force amplitude.

Control is done both on position and on velocity to obtain the smoothest arm positioning that will generate the less vibration. Both of them are controlled using a generic gain and a PID.

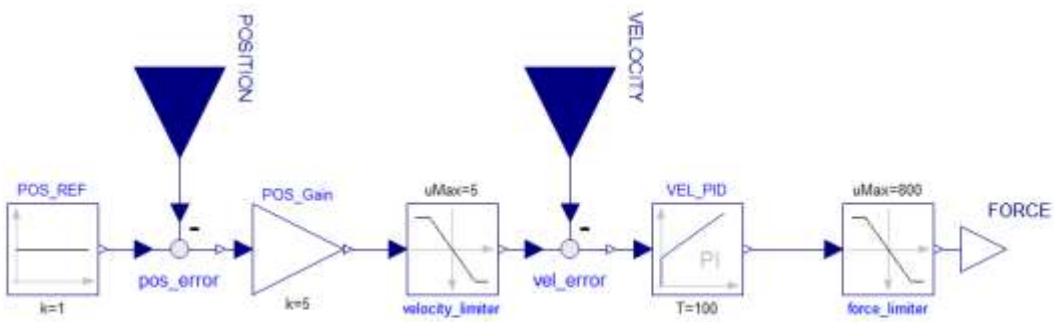

Figure 7. Dymola control model

Figure 7 shows the control model implemented with Dymola's environment. The controller compares the position response with a reference to compute the right force to apply on the arm. Velocity and force are limited to model a realistic system.

5. Results

Co-simulation is used to tweak controller's parameters that will minimize gantry robot's vibration as well as increasing its arm's positioning accuracy.

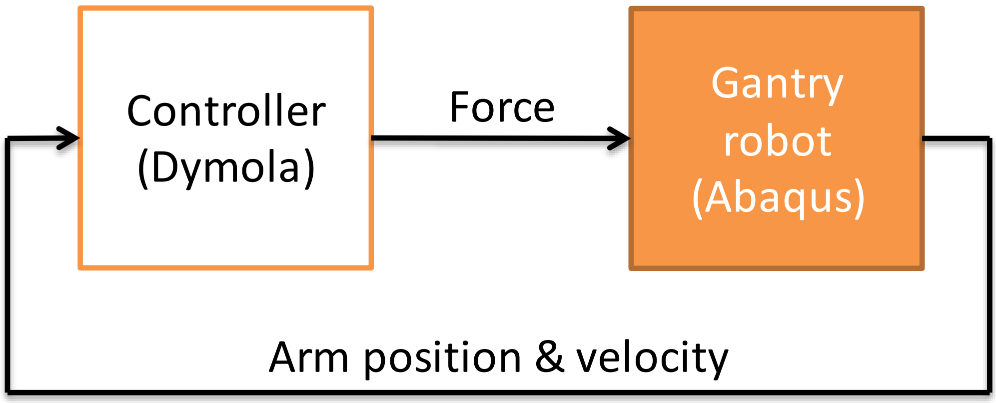

Figure 8. Model flow

Flow model described in Figure 8 is used for the co-simulation process. First simulations show that Gantry robot's response can be very unsatisfying when using a controller with random parameters (figure 9).

Another specific point is that a detailed physical model can be tremendously beneficial to correctly tweak a control model. Indeed if parameters, tweaked using a simple rigid mechanical model, are co-simulated with Abaqus model we can observe a bad response (figure 10).

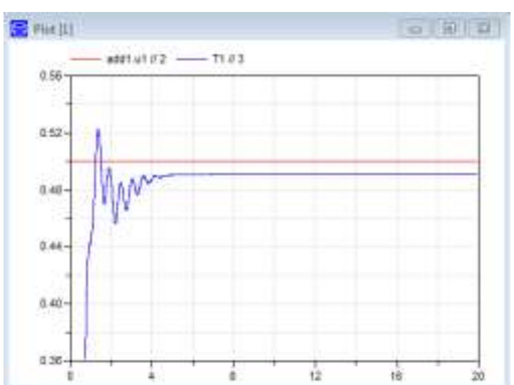

Figure 9. Positioning is not accurate.

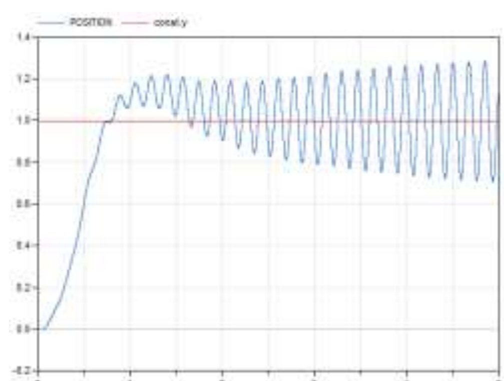

Figure 10. Very bad response diverging

Using PID tweaking technique, we can quickly find a good set of control parameters. Another solution is to integrate Abaqus-Dymola co-simulation technique to a PIDO software, such as Isight/SEE, to get a more robust parameters set.

Simulation results obtained with two different sets of parameters illustrate both methodologies (figure 11). They are both good candidates, however arm on the left graph is slightly oscilating and is slower than the arm on the right plot.

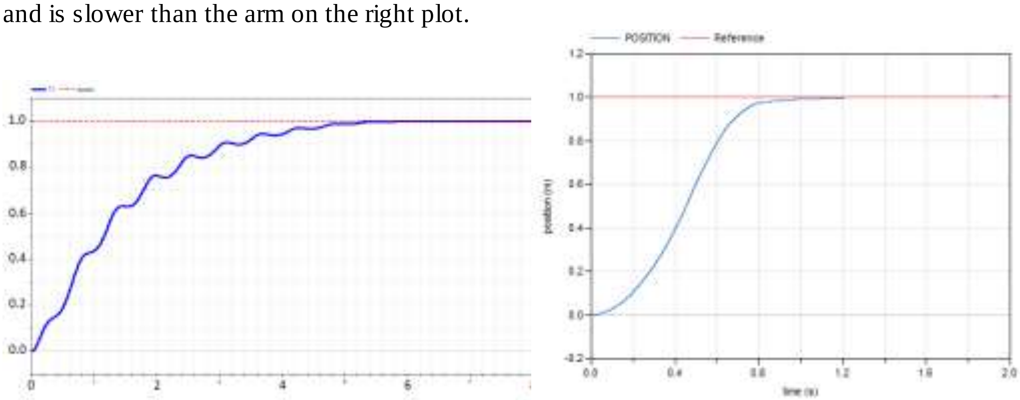

Figure 11. Arm positioning for two sets of parameters

6. Conclusion

We presented in this paper an application of the Abaqus-Dymolaco-simulation technique. This technique is very useful when physical model's accuracy has an influence on the control model. Abaqus is well suited to handle detailed model, as a matter of fact using Abaqus-Dymola co-simulation is an easy and convenient way to verify and validate the control part.

Regarding co-simulation, new features have been added to Abaqus 2016. Functional Mock-up Interface, known as FMI, can be a game changer player in the near future. Utilizing this standard we can couple Abaqus with a large variety of tools, such as Simulink, Flowmaster, Adams, and many more. Our future work intends to investigate further on Abaqus FMU capabilities.

7. References

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