LIMITATIONS OF HARDWARE-IN-THE-LOOP SIMULATIONS OF SPACE ROBOTICS DYNAMICS USING INDUSTRIAL ROBOTS

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ABSTRACT

The utilization of space robotics components in operational missions requires intensive pre-mission simulations, especially if dynamic influences will occur in the robotic manipulator, in its platform and the handled objects. Forces and torques are caused by manipulator activities and influences of the attitude control system of the satellite platform and lead to deformations and oscillations of elastic system components.

To cope with these problems in the first step software simulations of the kinematic and dynamic system behaviour have to be performed. Due to uncertainties in the modelling of tools, sensors and contact mechanics it would be advantageous to extend the simulation to a hybrid one integrating available flight hardware in the simulation loop. To simulate the manipulator's endeffector motion an industrial robot is used.

However integrating hardware requires real-time conditions of the simulation. Due to limitations of the sampling rate and dead times in the signal flow instabilities of the simulations may occur depending of the dynamics of the handled object.

1. INTRODUCTION

The efficient use of robotic manipulators for space applications requires intensive simulations on ground in order to guarantee for mission success, especially for mission critical manipulator operations such as deployment of the manipulator system, berthing of heavy loads and the use of tools under uncertain conditions. But also influences of the attitude control system during attitude correction manoeuvers of the satellite platform have to be considered. In all these situations strong dynamic effects occur. The forces and torques on the manipulator system lead to deformation of elasic mechanical components within the manipulator like joints and structural parts of the arm limbs.

The consequences are:

- failure of endeffector fine positioning tasks
- oscillation of the manipulator around an ideal trajectory
- undesired movement of handled components
- influences in the function of tools and working procedures.

To cope with these problems simulations on ground of the kinematic and the dynamic behaviour of the complete system during action are required. In the first step simulations can be performed in software. They may be sufficient in case of contact-free manipulator motions or on component level. But difficulties arise if the robotic tool itself and the contact mechanics between the tool and the handled object during operation have to be modelled. A similar problem is to model the behaviour of sensor systems and video based operations.

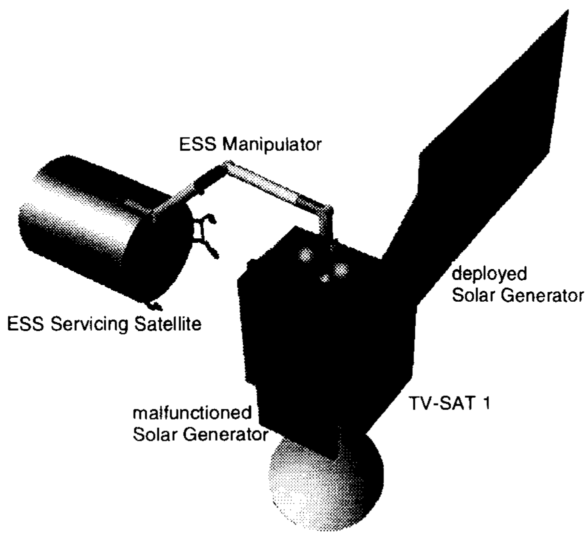

Figure 1: ESS Berthing Manoeuver

A typical example of space robotic based activities has been recently given by the German Experimental Servicing Satellite (ESS) study (Figure 1). Here, two relevant problems were encountered: First, the capturing and berthing of a non-cooperating target satellite (TV-SAT 1), and second, the use of a repair tool for cutting a clamping bolt that still prevents one of the solar generators from proper deployment and therefore the satellite from operation.

In such a case the modelling effort to implement a valid software simulation would increase tremendously. On the other hand, model simplifications are expected to falsificate the simulation results remarkably.

A very efficient solution to overcome these modelling problems is to make use of a hybrid simulation technique, where hardware parts, such as electro-mechanical tools are incorporated in the simulation

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

environment. Often, these parts are already available as breadboard models, prototypes or even as a space applicable version. Then, an industrial robot plays an important role as a generic motion system. Its only task is to carry hardware equipment of the overall simulation and to follow a trajectory calculated in the software part of the hybrid simulation loop.

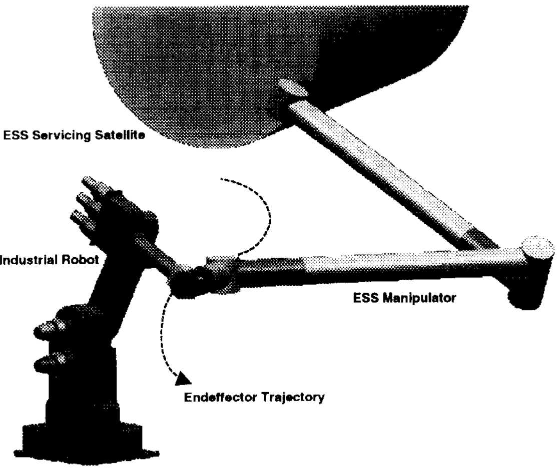

Figure 2: Physical Trajectory Display

Usually, the trajectory simulated by software is the one of the space manipulator endeffector, but every trajectory of interest can be commanded to the industrial robot equally. Figure 2 shows the industrial robot physically displaying an endeffector motion of the ESS manipulator by driving its own endeffector on

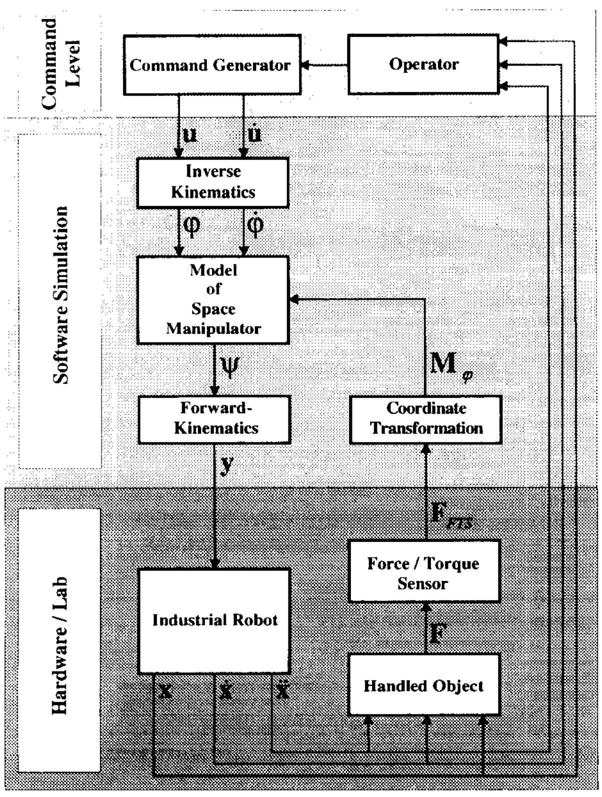

Figure 3: Signal Flow in the Simulation Loop

the simulated trajectory. It includes all dynamic effects such as joint oscillations, structural arm vibrations, interactions between the satellite base system and the moving manipulator and disturbances by the attitude control system of the satellite.

During contact phases, e.g. during the operation of endeffector tools, the equivalent forces and torques are measured by a force/torque sensor connected to the tool. The sensor signals are fed back to the software simulation and a new trjectory state vector is calculated whitch the industrial robot has to follow again. Figure 3 shows the signal flow inside the hybrid simulation set-up for an operator commanded system.

It has to be noticed that all software components of the simulation loop must be processable in real time, due to the fact that dynamic effects cannot be streched in the time space. So it has to be carefully proven, that the calculation accuracy is high enough even if the simulation time steps are coarser compared with off-line, non real time simulations.

2. CONCEPT TESTS

In the very first steps of the realization of the hybrid simulation concept, a large manipulator with elastic joints was modelled and its motion was calculated in software. Its endeffector was driven physically displayed by the endeffector motion of the industrial robot in the lab. The task was to touch and to push the endeffector against elastic material like rubber foam or a sheet metal of copper (Figure 4).

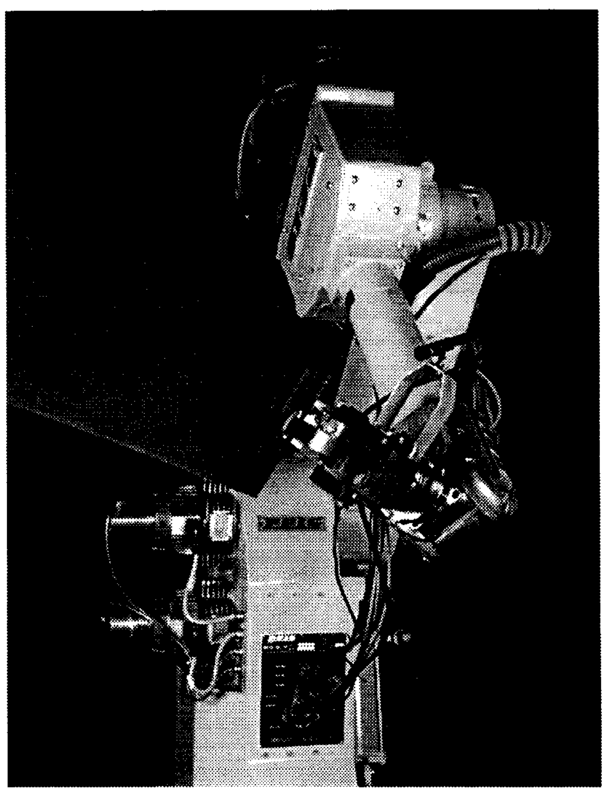

Figure 4: Industrial Robot Touching Elastic Material

In this conceptual phase it was found that in some situations the simulation becomes unstable depending on the dynamic properties of the handled object. This was surprising because the simulated maipulator system was a passive one without any controller influences.

To find the reasons for this problems the dynamics of the industrial robot was analyzed. The most important features are

- the dynamic transfer behaviour of the whole robot system and
- the time delay in executing commands.

Concerning the amplitude transfer function it was found that the robot has an almost ideal behaviour in the working volume of relevant kinematic configurations (Figure 5). In the frequency range up to 5 Hz the robot shows a small linear increase of the amplitude ratio. But this deviation is easy to filter so that we can consider the robot as an ideal transmitter in the range less than 5 Hz.

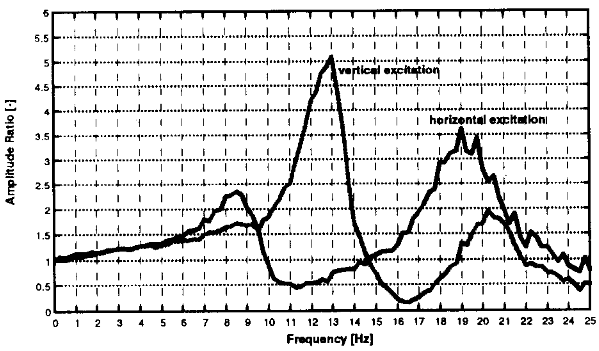

Figure 5: Transfer Function of the Industrial Robot

The time delay between sending the command and executing the motion depends on the interface between the software simulation and the robot controller. Using a high level interface with a command rate of 50 Hz the time delay is 40 ms. In case of removing control functions from the robot controller to the simulation set-up a command rate of 400 Hz is required. In this mode the dead time can be reduced down to 17.5 ms (Figure 6).

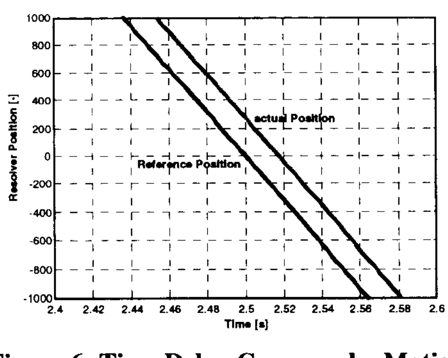

Figure 6: Time Delay Command – Motion

3. MODELLING OF THE SIMULATION SET-UP

To verify the effects of unstable simulations theoretical investigations were performed. In this step the complete hybrid simulation was modelled in software only, including all parts originally integrated in hardware. This provides an easy way to perform parameter variations of all interesting aspects of the simulation set-up.

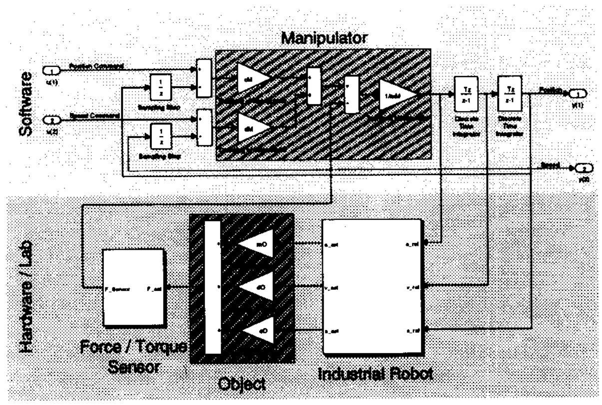

Figure 7: Block Diagram of the Hybrid Simulation

Figure 7 shows the block diagram of the software representation of the hybrid simulation for 1 degree of freedom. In the software layer the dynamic properties of the simulated manipulator and the time integration for the motion calculation can be found. The hardware layer includes all parts usually realized in hardware. In this example these are the industrial robot with its transfer behaviour, the dynamic properties of an object to be gripped and a force / torque sensor. The simulation loop is closed via sensor data feed back to the manipulator motion calculation.

To perform the investigation with a realistic data base the scenario of the ESS study (Figure 1) was used. The defined task to be simulated was to grip the deployed solar generator. There were two steps to reduce the dynamic model. First, the ESS manipulator was reduced to a two link manipulator (2 pitch links) with elastic joints. It includes the geometrical properties as well as the dynamic properties like masses, elasticity and damping.

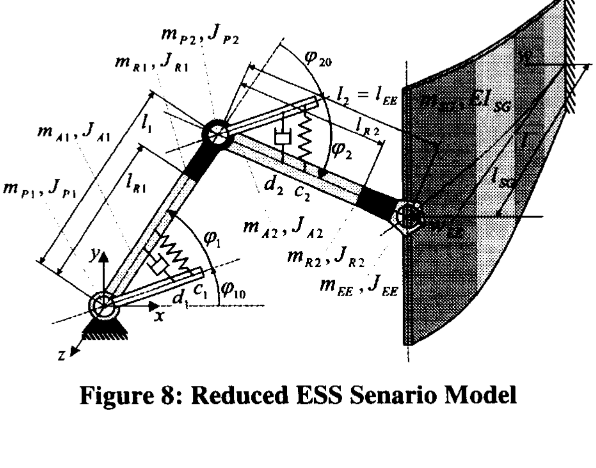

Figure 8: Reduced ESS Senario Model

The model of the solar generator is a flexible beam with dynamic properties of the original one (Figure 8). In the second step of model complexity reduction it is assumed that endeffector motions appear only in one direction, namely the deflection direction of the solar generator. In this case the joint positions φ_1 and φ_2 are not independently to be chosen. Thus the manipulator is described as a dynamic system with 1 degree of freedom. Assuming that for simulation aspects only the first oscillation mode of the solar generator is relevant, it can be reduced also to a system with 1 degree of freedom. The result of model complexity reduction is shown in Figure 9. In the following text the handled system, e.g. the solar generator, is more generally called object.

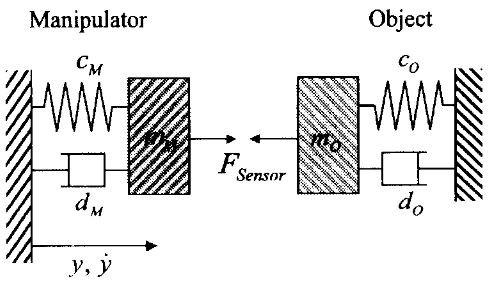

Figure 9: System with 1 Degree of Freedom

The parameters of the dynamics of the 1 DOF system (Figure 9) can than transfered to the according blocks in the block diagram of Figure 7. The internal forces between the manipulator and the object are not theoretically calculated. They are measured and depend therefore on the dynamic behaviour of the force / torque sensor and the industrial robot which follows the manipulator trajectory. The estimation of the system behaviour is based on calculations of the system eigenvalues. The operating point is defined by both position 0 and speed equal to zero.

4. SIMULATION RESULTS

The interest in the simulation results is focused on the stability of the simulation. Therefore the main aspect of result processing is to define ranges of dynamic properties of the handled objects which fit to the simulated manipulator so that the complete system can be simulated without getting unstable. Figure 10 shows the eigenvalus of the system in the z-plane which is commonly used to display results of time discrete systems. For a stable simulation all eigenvalues have to be inside the unit circle. As a reference marked with stars the Figure shows the pairs of complex eigenvalues of the simulated manipulator itself and the coupled system manipulator-object as found for a time-continuous, dead time free simulation. The influence of the object in the system dynamics can be derived from the distance between the eigenvalues of the manipulator and the coupled system. Being marked with dots the eigenvalues of the coupled system are shown using a sampling rate of 50 Hz and a dead time of 60 ms (40 ms dead time of the industrial robot, 20 ms for sensor data feed back). For each additional sampling time step of dead time a new eigenvalue (or a pair of complex eigenvalues) appears.

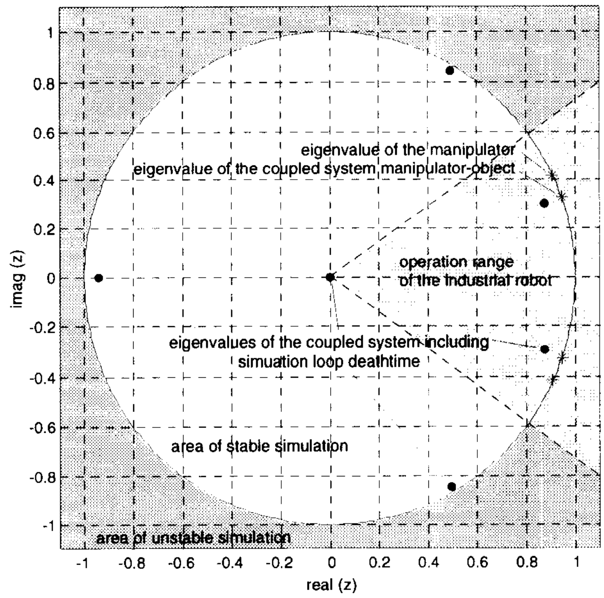

Figure 10: Eigenvalues using 50 Hz Sampling Rate

The corresponding results applying a sampling rate of 400 Hz with a dead time of 20 ms (17.5 ms dead time of the industrial robot, 2.5 ms for sensor data feedback) are shown in Figure 11.

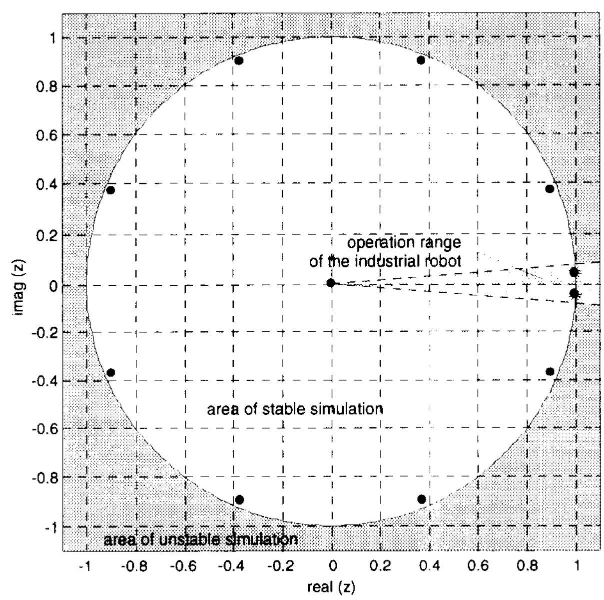

Figure 11: Eigenvalues using 400 Hz Sampling Rate

It was found that in both cases of sampling rates the simulation could be performed without instabilities. But it has to be considered, that these results are based on an extreme reduction of the model complexity and therefore are to be regarded with some uncertainties. A proper way to find a satisfactory operation range for a simulation is to vary the dynamic properties of the handled object and to recalculate the eigenvalues. A way to display this kind of parameter variation in an easy to interprete manner is to show the absolue values of the eigenvalues (*abs(z)*) over, first, the ratio of eigenfrequency of the coupled system to the eigenfrequency of the manipulator (ω/ω_M), and second, over the non-dimensional damping rate of the coupled system. The system eigenfrequencies were varied either by changing the object elasticity or the object mass.

The vertical wall in Figure 12, Figure 14 and Figure 16 shows the operation limit (damped eigenfrequency of 5 Hz) of the industrial robot for an application as a physical motion generator inside the hybrid simulation. All systems which can be described by dynamic parameters being located on the left hand side of the limit wall could be displayed by the industrial robot.

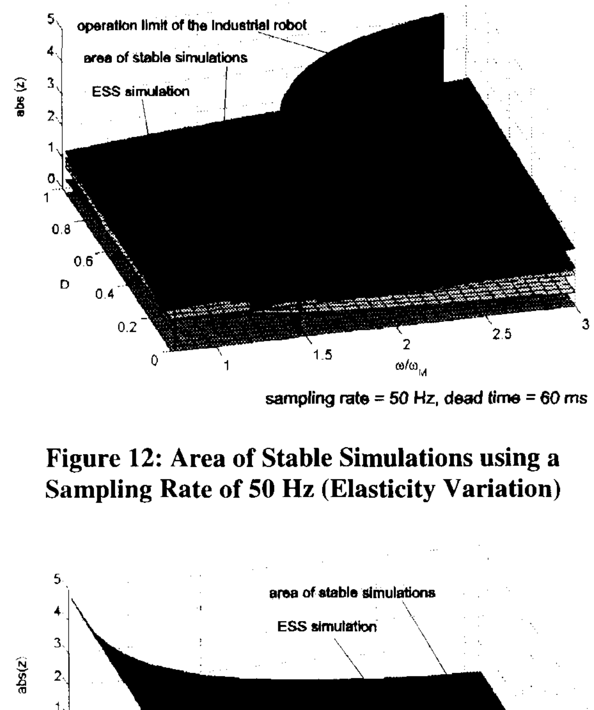

Figure 12: Area of Stable Simulations using a Sampling Rate of 50 Hz (Elasticity Variation)

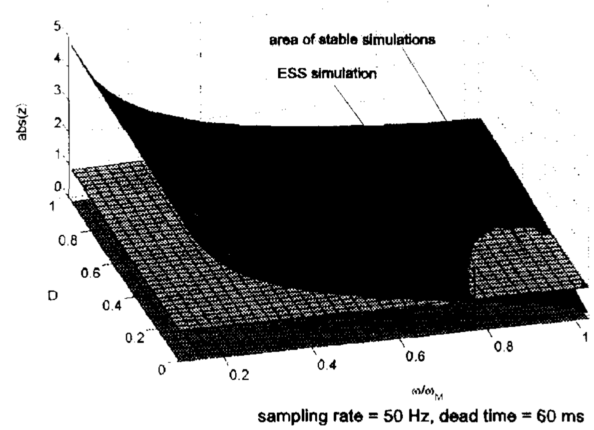

Figure 13: Area of Stable Simulations using a Sampling Rate of 50 Hz (Mass Variation)

Figure 12 and Figure 13 show that for a sampling rate of 50 Hz with a simulation facility depending dead time of 60 ms inside the simulation loop only a very small area of system dynamics variation is left to perform stable simulation within. Only there the plane abs(z) = 1 is higher than all planes of the absolute values of the eigenvalues. It is just a good luck that the ESS-Simulation fits the dynamic properties to stay inside the valid area. Generally, it has to be remarked that in the operation mode mentioned above a closed loop hybrid simulation is not possible.

A much better situation is found in the second operation mode of the simulation facility (Figure 14 and Figure 15). In this case a sampling rate of 400 Hz is used in all parts of the simulation loop. The dead time within the loop is 20 ms. It is shown that in a wide range of dynamic system properties the simulation stays in a valid area. This area partly extends the frequency bandwidth that is able to be physically displayed by the industrial robot. However, it has to be noticed that for the example of the ESS scenario the simulation is also not far away from the limit of stability. Especially this is to be seen in Figure 15, where the object mass was varied to change the system eigenfrequencies.

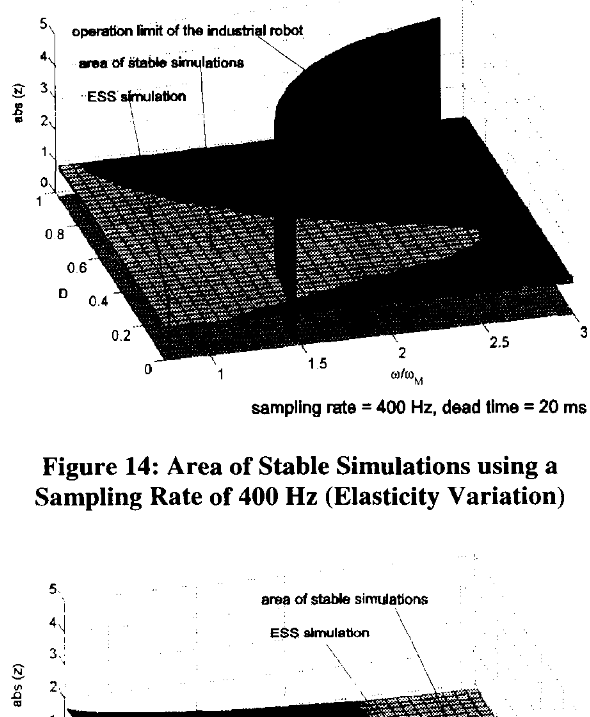

Figure 14: Area of Stable Simulations using a Sampling Rate of 400 Hz (Elasticity Variation)

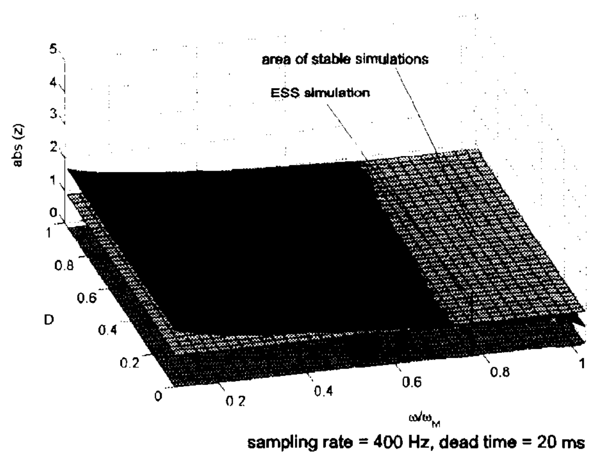

Figure 15: Area of Stable Simulations using a Sampling Rate of 400 Hz (Mass Variation)

A further aspect which has to be mentioned is the dead time inside the simulation loop. Mostly this time delay depends on hardware equipment of the simulation facility. In this case the main reason for dead times in the loop is the control of the industrial robot. So reductions of dead times would require to impact into the robot's drives, its internal electronics and control strategies. But this cannot be performed during the development of simulation concepts.

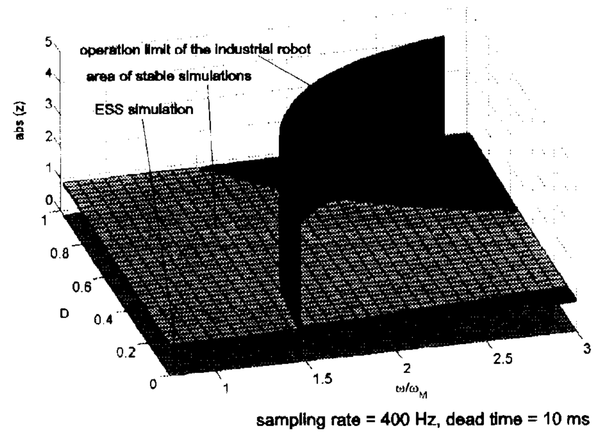

Figure 16: Area of Stable Simulations with Reduced Time Delays (Elasticity Variation)

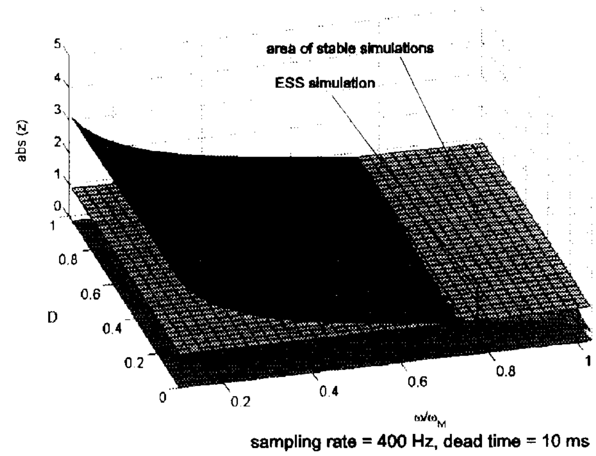

Figure 17: Area of Stable Simulations with Reduced Time Delays (Mass Variation)

However, theoretical investigations were performed to demonstrate the effect of reducing dead times in the loop. Figure 16 and Figure 17 show the results for half a dead time of the original one. The range of stable simulations can therefore be further extended but it has to be noticed, that not the complete operational range of the industrial robot is inside the valid area.

Assuming realistic values for sampling rates and dead times reachable for space robotics simulation the stable area defined above cannot be extended essentially. There are still limits concerning computer power and the dynamics of hardware equipment. If the hybrid simulations condition do not match the dynamic conditions for stable simulations, additional signal processing inside the simulation loop havs to be performed. For the system example mentioned in this paper, methods of software energy dissipation during the simulation run have to be developed. This could be performed by appropriately processing the sensor data fed back into the software simulation.

5. CONCLUSION

In this paper a method was presented to simulate space robotics operations. The simulation method is a hybrid one which combines the advantages of software simulations and hardware test set-ups. Due to the integration of an industrial robot it is possible to display simulated motions physically and to move tools, sensors and other harware equipment. An important feature is the sensor data feedback into the software simulation to realize a closed loop simulation. However limitations in the sampling rate and dead times in the loop in some cases cause instabilities of the simulation. In opposite to off-line simulations, real-time conditions have to be maintained and a problem solution by a refinement of the simulation step size is not valid. The appearence of instabilities depends on the dynamic properties of the simulated system. Generally, an increasing sampling rate and a reduced dead time in the simulation loop extend the dynamic range of stable simulations. However, assuming realistic values for sampling rates and dead times there are still areas of instability wherein the hybrid simulation method is not suitable.

6. LITERATURE

[1] B. Schäfer, R. Krenn; *Force/Torque Sensor Feedback Measuring Contact Dynamics in Space Manipulator Hybrid Simulation*; AIAA Guidance, Navigation and Control Conference, Portland, Oregon, USA, 9-11 August 1999.

[2] B. Schäfer, M. Lösch, K. Landzettel; *Simulation of Manipulator Deployment and Satellite Capturing Dynamics*; Astra Workshop, ESTEC, Noordwijk, The Netherlands, 1-3 December 1998.

[3] R. Krenn, B. Schäfer; *Instabilitäten in Simulationen bei Rückführung von Kraft-Momenten-Signalen*; GAMM annual meeting, University of Bremen, Germany 6-9 April 1998.

[4] R. Krenn, M. Lösch, B. Schäfer; *Industrieroboter als flexibles Werkzeug in der Echtzeit-Simulation von Raumfahrtmanipulatoren*; VDI Berichte 1315 (1997), Page 217-231.